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2020 LIFE CYCLE ASSESSMENT OF U.S. AVERAGE CORRUGATED PRODUCT

FULL REPORT

Prepared by:

National Council for Air and Stream Improvement, Inc.

Anthesis

Prepared for:
Corrugated Packaging Alliance (CPA)
A joint venture of
American Forest & Paper Association (AF&PA)
Fibre Box Association (FBA)
AICC, The Independent Packaging Association (AICC)
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PROJECT INFORMATION	
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ACRONYMS AND ABBREVIATIONS

Organizations:

AF&PA:	American Forest & Paper Association
AICC:	AICC, The Independent Packaging Association
CORRIM:	Consortium for Research on Renewable Industrial Materials
CML:	Centre of Environmental Science at Leiden
CPA:	Corrugated Packaging Alliance
FBA:	Fibre Box Association
ISO:	International Organization for Standardization
NCASI:	National Council for Air and Stream Improvement
NREL:	National Renewable Energy Laboratory
PE:	PE Americas
U.S. EPA:	United States. Environmental Protection Agency
WBCSD:	World Business Council for Sustainable Development
WRI:	World Resources Institute

General:

AOX:	Adsorbable organic halides
BCTMP:	Bleached chemi-thermomechanical pulp
BK:	Bleached kraft
BKD:	Bleached kraft dissolving
BKI:	Bleached kraft, integrated
BKMP:	Bleached kraft market pulp
BKO:	Bleached kraft, other
BOD:	Biochemical oxygen demand
CFCs:	Chlorofluorocarbons
CFS:	Commodity Flow Survey
CHP:	Combined heat and power
CP:	Corrugated product
COD:	Chemical oxygen demand
DNWS:	Deinked newsprint

DTF:	Deinked tissue/fine papers
EH&S:	Environment, Health and Safety
EI:	ecoinvent
EoL:	End-of-life
eq.:	Equivalent
FU:	Functional unit
GHG:	Greenhouse gas
GWP:	Global warming potential
HFCs:	Hydrofluorocarbons
HHV:	Higher heating value
IUR:	Inventory Update Reporting (U.S. EPA)
LCA:	Life cycle assessment
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment
LHV:	Lower heating value
MECH:	Mechanical
NIF:	Non-integrated fine or lightweight papers
NIO:	Non-integrated other papers
NOU:	Number of Uses
NOx:	Nitrogen oxides
OCC:	Old corrugated containers
odst:	Oven-dried short ton
P&P:	Pulp and paper
P&PO:	Pulp and papermaking operations
PM:	Particulate matter
PWM:	Production-weighted mean
PS:	Pulp substitutes
RBOX:	Recycled boxboard
RCTR:	Recycled containerboard
RDI:	Recycled deinked newsprint and fine paper
RNDI:	Recycled non-deinked

RTF:	Recycled tissue/Fine paper
SC:	Semi-chemical
SCTG:	Standard Classification of Transported Goods
SULD:	Sulfite dissolving pulp
SULF:	Sulfite paper grade
ton:	Short ton
TRACI:	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRI:	Toxic Release Inventory (U.S. EPA)
TRS:	Total reduced sulfur
TSS:	Total suspended solids
UBKMP:	Unbleached kraft market pulp
UK:	Unbleached kraft
UVB:	Ultraviolet-B radiation
VOC:	Volatile organic compound
WWTP:	Wastewater treatment plant

Country/Region Codes used in Datasets:

CH:	Switzerland
DE:	Germany
EU-27:	European Union, not including Croatia
GLO:	Global
NC:	U.S. Northcentral
NE:	U.S. Northeast
RNA:	North America
SE:	U.S. Southeast
US:	United States

Impact Categories and Other Indicators:

AP:	Acidification
ECO:	Ecotoxicity
EP:	Eutrophication
FF:	Abiotic resource depletion, fossil fuel

GW:	Global warming, F: flow accounting, S: stock accounting, Excl. BioCO_2: excluding biogenic CO_2
HHC:	Human health cancer
HHNC:	Human health non-cancer
NRPE:	Non-renewable primary energy demand
ODP:	Ozone depletion
POCP:	Photo-chemical oxidation/Photo-chemical ozone creation
RES:	Respiratory effects
RPE:	Renewable primary energy demand
WC:	Water consumption
WU:	Water use (Water withdrawal in ISO 14046 (2014))

TECHNICAL SUMMARY

TS1. Background and Objective

The Corrugated Packaging Alliance (CPA), a joint venture of the American Forest & Paper Association (AF&PA), Fibre Box Association (FBA), The Independent Packaging Association (AICC), and TAPPI, have commissioned NCASI to conduct a life cycle assessment (LCA) study of the 2020 U.S.-average corrugated product. There were three main objectives of the study:

1) To educate customers and stakeholders about the environmental attributes of the industry's corrugated packaging produced in 2020;
2) To contrast, to the extent possible, the updated results with those of 2006, 2010, 2014, and 2020; and
3) To present the environmental performance of a corrugated product made of 100%-recycled fiber relative to that of a product made using the industry-average recycled content.

The study follows the principles described in the ISO 14040 Standard (ISO 2006a) and has been conducted according to the requirements of the ISO 14044 Standard (ISO 2006b).

The study being an update of the 2014 LCA published in 2017 was reviewed by one external reviewer instead of a panel. The reviewer was Lindita Bushi, PhD, from Athena Sustainable Materials Institute. The critical review in no way implies that the reviewer endorses the results of the LCA study, nor that they endorse the assessed products. It ensures that the study, among other requirements, was carried out per the provisions of the ISO standards.

TS2. Products Studied

Four different products manufactured and used in the U.S. were studied in this assessment:

1. The 2020 U.S. industry-average corrugated product (main product studied in this LCA) (*new*);
2. The 2014 U.S. industry-average corrugated product;
3. The 2010 U.S. industry-average corrugated product;
4. The 2006 U.S. industry-average corrugated product;
5. The 2020 U.S. industry-average corrugated product made from 100%-recycled fiber (*new*); and
6. The 2014 U.S. industry-average corrugated product made from 100%-recycled fiber.

Corrugated products (for instance, corrugated boxes) are made of corrugated board (combined board). Corrugated board is the structure formed by bonding one or more sheets of fluted corrugating medium to one or more flat facings of linerboard.

The 2020 U.S.-average corrugated product studied in this LCA consists of 66.0% linerboard and 34.0% corrugated medium, with an average basis weight of 123.4 lb/thousand square feet (msf, 0.602 kg/m^2). The industry-average containerboard utilizes about 56% recovered fiber, primarily from recycled old corrugated containers (OCC), with the balance supplied mostly by kraft and semi-chemical pulp. More information regarding the 2014, 2010, and 2006 product can be found in the LCA reports from prior assessments (https://www.fibrebox.org/life-cycle-assessments). ISO 14044 requires that whenever two products are compared, these should be functionally equivalent. For that reason, the 100%-recycled product studied in this assessment, and compared to the industry-average, was modeled using the same board mix (linerboard to medium ratio) and the same basis weight as the industry-average product.

TS3. The Study Design and Methods Employed

The functional unit for the study was ***"the domestic use of 1 kg of an average corrugated product produced in the U.S. in 2020."*** The system boundary included the entire life cycle of the corrugated product, extending through manufacturing, use, recovery, and end of life, as shown in
Figure 1. The product system was separated into four life cycle stages:

1) **Pulp and papermaking operations**, including forest operations, transportation of wood to chipping, transportation of recovered fiber to the facility, off-site chipping, on-site production of chips, off-site production of market pulp, production of on-site produced pulp, papermaking operations (to produce containerboard), conversion into rolls, offsite production of purchased chemicals, fuel, and energy, and supporting activities (on-site steam and power production, on-site chemical production, effluent treatment, on-site waste management, offsite effluent treatment at publicly owned treatment works (POTW), etc.).
2) **Converting**, including the activities involved in converting the linerboard and corrugating medium into corrugated packaging.
3) **Use**, including transportation to the use phase but excluding energy and resources used during the use life cycle stage and the waste generated from use other than the product itself.
4) **End-of-life**, including end-of-life management of the packaging product (landfilling, burning with energy recovery).

Each life cycle stage is supplied by resources and necessitates residual management. Transportation between two life cycle stages is included in the downstream stage.

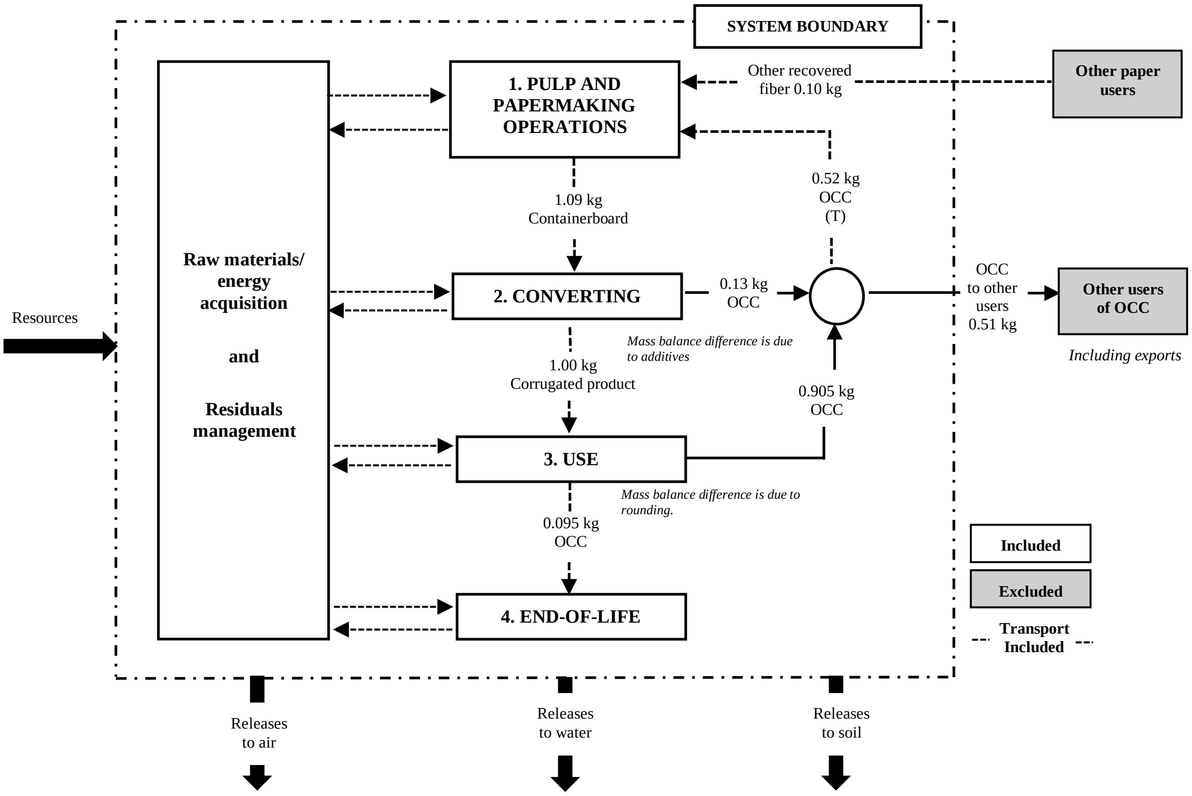

Figure 1. System Boundary for the Corrugated Product System

Instead of applying cut-off criteria for data completeness, attempts have been made to be as comprehensive as possible. The data for the study were obtained from the following sources:

- Data on water inputs, environmental loads, solid waste management, and energy (quantity and types of fuels) for the relevant pulp and paper mills were drawn from responses to the 2020 AF&PA Environmental, Health, and Safety Survey.
- Information on quantity of energy used, fiber input, furnish production, and chemical consumption (quantity and type) at the department level was collected in a supplemental survey.
- Data regarding the emissions of toxic substances (as defined by the U.S. Toxic Release Inventory) were modeled using U.S. LCI and NCASI information.
- Data on nutrient content of treated wastewater effluents from pulp and paper mills were derived from available information in the U.S. EPA Permit Compliance System database (www.epa.gov/enviro/html/pcs/); these data are insufficient to allow characterization of effluents from the specific mills in the database, but they do allow general characterization of effluents from U.S. pulp and paper mills.
- Data submitted by the industry in connection with the TSCA Inventory Update Rule (IUR, www.epa.gov/iur/) were used to estimate quantities of kraft pulping co-products (e.g., turpentine and tall oil) produced; the IUR data were not sufficient to characterize every mill in the database but were sufficient to characterize kraft pulping processes in general.
- Converting facilities in the U.S. were surveyed to collect energy and material input, production, and environmental release information.

- Data and models for other aspects of the life cycle (e.g., for landfills) were obtained from a number of government sources, public life cycle databases (U.S. LCI, GaBi, *ecoinvent*), and published studies.

Where allocation was needed to address co-products, the allocation was done using what was considered to be the most suitable method available, with alternative methods being used in sensitivity analyses, as appropriate.

The investigated product system is a hybrid of a closed-loop and open-loop product system because both closed-loop and open-loop recycling occur in the product system. Recycling of converting wastes and old corrugated containers within containerboard production can be described as closed-loop recycling, while imports and exports of recovered fiber to and from the investigated product system are cases of open-loop recycling. An allocation method is required to deal with open-loop recycling. Two different recycling allocation approaches were used in this study: 1) Closed-Loop Approximation combined with the Cut-Off Method, and 2) the ISO 14049 Number of Uses (NOU) Method.

The first approach (Closed-Loop Approximation w/Cut-Off Method) was used to characterize the environmental loads of the industry-average product. Using this approach, it was assumed that the entire requirement for recovered fiber in containerboard production was fulfilled from converting wastes and old corrugated containers recovered at their end-of-life (i.e., closed-loop recycling). In other words, no other recovered fiber sources (e.g., mixed papers) were considered <u>for allocation purposes</u> and hence no environmental load from other product systems was brought within the system boundary. In doing so, there was a net export of recovered fiber to other systems because more old corrugated containers are recovered than the containerboard production process actually needs. It was assumed that this net export of recovered fiber leaves the system boundary without an environmental load associated with it (i.e., a cut-off method was used, and all the environmental load is considered to be within the system). This allocation method was retained as the main one for this study because it represents the direct environmental load of a product system and is also the method that is aligned with existing life cycle inventory databases.

However, the choice of an allocation approach for recycling can be critical for comparing paper products with different recycled fiber contents (e.g., Galeano et al. 2011, NCASI 2012), which in addition to documenting the environmental performance of the studied products was a second objective of this study. For this reason, two different approaches were used to express the environmental load of the 100%-recycled content product relative to that of the industry-average recycled content product, each of which provides a different perspective on how the environmental load of fresh fiber production processes is shared between all usages of the fiber (i.e., fresh fiber and recycled). The first approach used was the Closed-Loop Approximation with Cut-Off Method described above. The second approach employed was the Number of Uses (NOU) Method described in the ISO 14044 Standard and its accompanying Technical Report (ISO 14049). This second approach was selected for several reasons. Among them is a recommendation from an international working group addressing life cycle inventory issues, as included in a 1996 report by AF&PA (Life Cycle Inventory Analysis User's Guide - Enhanced Methods and Applications for the Products Industry), that this method be used in LCA studies of paper because it is the only one that reflects the complex interactions between fresh fiber and recycled fiber. The main difference between the two methods is that the Cut-Off Method assigns the environmental loads and benefits from fresh fiber material production to the products made of fresh fiber only, while the Number of Uses Method shares the loads and benefits between the product made of fresh fiber and those made of recycled fiber.

Data collection questionnaires were sent to all containerboard facilities member of either AF&PA or NCASI and to all converting facilities member of FBA. The study was based on information from 51 containerboard mills representing 69% of 2020 U.S. containerboard production and 402 converting facilities representing 57% of overall containerboard converting production volume for 2020.

The life cycle modeling was done using the GaBi^{TM} software package. Environmental impacts were characterized using the TRACI impact assessment method developed by U.S. EPA, using the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR6) factors for global warming. In accordance with accepted greenhouse gas accounting practices, biomass-derived CO_2 was tracked separately from fossil fuel-derived CO_2 and other greenhouse gases in the life-cycle inventory. The effects of biomass carbon on the atmosphere were characterized by calculating the net emissions of biogenic CO_2 (emissions minus removals), which were then added to the global warming results. This approach, referred to as flow accounting, was also used in the previous LCA studies. In addition, impact indicator results were developed for the following indicators: ozone depletion, photochemical oxidation (smog), acidification, eutrophication, and fossil fuel depletion. Impacts on biodiversity were not quantified as there is no consensus method suitable for forest management. The CML 2001 (2016 revision) impact assessment method developed in the Netherlands was used to test the sensitivity of the acidification, eutrophication, and smog indicators. Results were also developed for the following additional inventory indicators: non-renewable primary energy demand and renewable primary energy demand, based on the method available in GaBi^{TM}, and calculated from higher heating values found in Table 15, as well as water use and water consumption based on life cycle inventory data. Renewable primary energy demand excluded the intrinsic feedstock energy (heat of combustion) of any raw material input that is not used as an energy source in the studied product systems.

Sensitivity analyses were performed on various aspects.

TS4. Results

This section summarizes the results obtained from this LCA.

TS.4.1 2020 Results: LCIA Profile

The cradle-to-grave life cycle impact assessment (LCIA) results obtained by applying TRACI, the IPCC factors for global warming, and GaBi non-renewable and renewable primary energy demands are shown in Table 1.

The results show that pulp and papermaking operations (primarily containerboard production) are the main contributor to all impact categories except global warming. More detail on the global warming indicator is provided in the next section. Converting is also a significant contributor to most other indicators. End-of-life contributes significantly to the global warming indicator results, but only when the flow approach is used for biogenic carbon accounting. Finally, the use phase (which primarily reflects the impacts of transportation) does not contribute significantly to impact categories.

Table 1. LCIA Results per Functional Unit

Impact category	**Unit/FU**	**Total**	**Life Cycle Stage Contribution**			
			1. Pulp and Papermaking Operations	**2. Converting**	**3. Use**	**4. EoL**
Impact Assessment Indicators						
Global warming, flow accounting*	kg CO_2 eq.	0.414	-7.8%**	46.0%	6.0%	55.8%
Ozone depletion	kg CFC-11 eq.	6.22E-08	90.4%	8.9%	0.7%	0.1%
Photo-chemical oxidation (smog)	kg O_3 eq.	0.090	76.1%	17.9%	4.6%	1.4%
Acidification	kg SO_2 eq.†	8.73E-3	81.7%	14.4%	1.5%	2.4%
Eutrophication	kg N eq.†	9.27E-4	83.7%	10.8%	0.9%	4.6%
Respiratory effects (particulates)	kg $PM_{2.5}$ eq.	7.17E-4	90.9%	8.3%	0.3%	0.6%
Fossil fuel depletion	MJ surplus	2.17	75.1%	22.4%	2.1%	0.5%
Additional Inventory Indicators						
Non-renewable energy demand	MJ	23.42	78.4%	19.9%	1.4%	0.4%
Renewable energy demand‡	MJ	18.27	75.0%	22.7%	1.8%	0.4%
Water use	kg	43.36	88.4%	11.4%	0.0%	0.2%
Water consumption	kg	10.58	56.2%	43.1%	0.0%	0.7%

*NOTE: Percentages not adding up to 100% is due to rounding. *The flow accounting approach was also used in the previous LCA studies. **Number is negative because it includes carbon sequestration in wood inputs. †Total of air and water. ‡Excluding feedstock energy.*

TS.4.2 2020 Results: Details on Global Warming

This section presents more details on the global warming indicator. Figure 2 presents how each life cycle stage contributes to greenhouse gas (GHG) emissions. From this figure, the following can be observed:

- Pulp and papermaking is the greatest contributor to all GHG emissions and removals.
- Removals (primarily due to biomass grown to produce containerboard) offset a large proportion (71%) of all GHG emissions (biogenic CO_2 and other GHGs).
- Emissions of biogenic CO_2 occur mainly at pulp and paper mills.

- Emissions of other GHGs are spread out across pulp and papermaking operations, converting, and end-of-life stages.
- Overall, the main contributors to the total global warming indicator are converting and end-of-life.

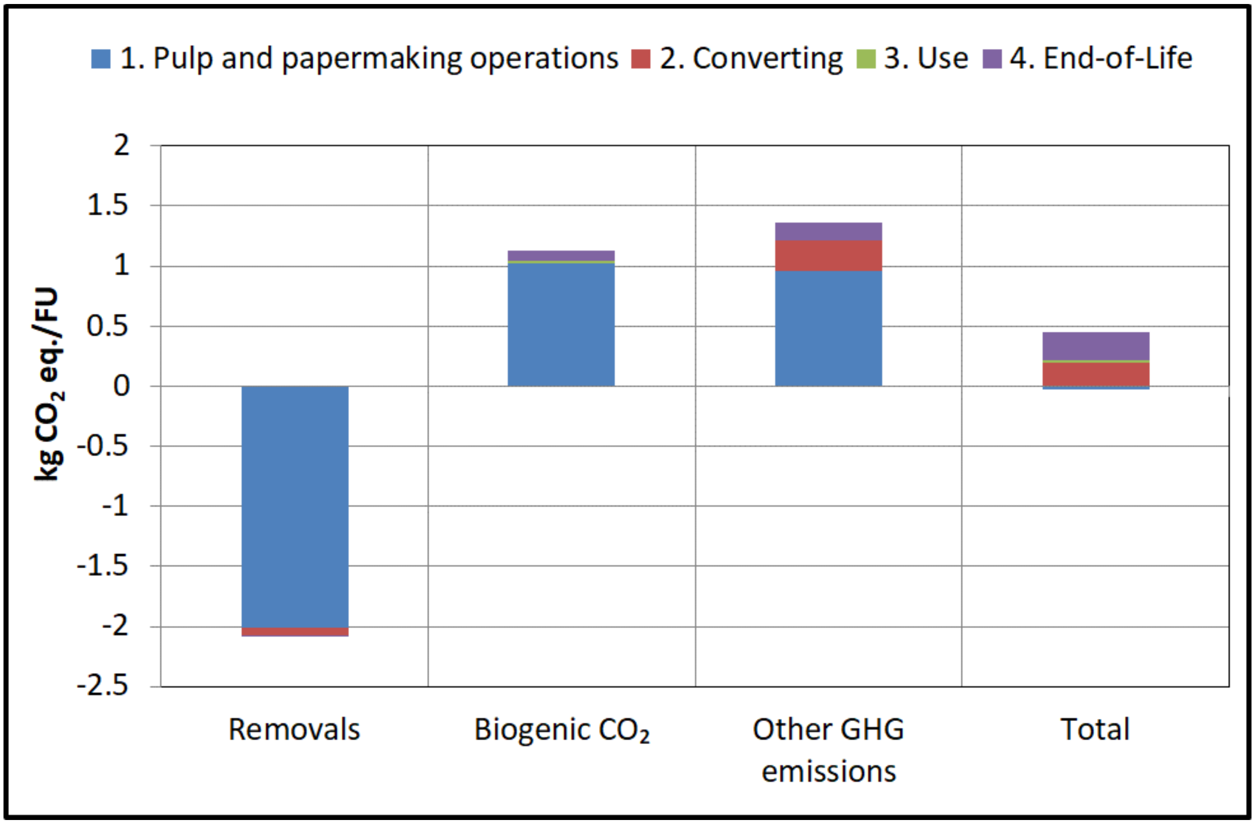

Figure 2. Contribution of the Life Cycle Stages to GHG Emissions

Within the pulp and papermaking operations life cycle stage, forest operations are responsible for removals while energy production is the main process responsible for biogenic CO_2 and other GHG emissions. The rest, for instance chemical production and residuals management, do not contribute significantly to the global warming indicator.

On the converting side, while some removals are associated with chemical (starch) usage, there are very low emissions of biogenic CO_2 because converting facilities do not typically use biomass fuels. A fraction of the biogenic carbon associated with starch is released at the end of life. Other GHGs are distributed across energy (primarily purchased electricity and natural gas), transportation of the containerboard to converting facilities, and chemicals (primarily starch and ink).

At end-of-life, methane from landfills is the main contributor to the global warming indicator. The 2010 study showed that results for the global warming indicator were sensitive to assumptions regarding landfill gas recovery and burning. The sensitivity analysis was not repeated in this study, but the effect is expected to be somewhat less important than in previous studies because less corrugated product was landfilled in 2020 than in 2010.

Overall, there are more removals than biogenic CO_2 emissions within the product system because 1) a portion of the removed carbon is released as CH_4, and another portion is stored in landfills, and 3) a significant portion of the used containerboard is exported outside the system boundary (with the cut-off allocation method, the carbon removal remains within the system boundary).

TS.4.3 2020 Results: Sensitivity Analyses

Sensitivity analyses were performed on various aspects. Some observations from these are as follows.

As illustrated in Figure 3, the global warming indicator results are sensitive to the approach used to calculate emissions of biogenic CO_2:

- Flow accounting (GW,F) gives the lowest carbon footprint because it includes the gross carbon removal associated with wood inputs, with a significant portion of the used corrugated product exported to other product systems (i.e., associated with no emissions within the studied system boundary).
- Stock accounting (GW,S) considers the change in landfill carbon stock to calculate the net biogenic CO_2 implication. This approach results in lower total carbon removal compared to the flow accounting approach because very little corrugated product ends up in landfills.
- Excluding biogenic CO_2 (GW, Excl BioCO_2) gives slightly higher number than GW,S because net carbon storage is ignored.

The difference in carbon accounting for biogenic CO_2 are further discussed in Section 5.2.

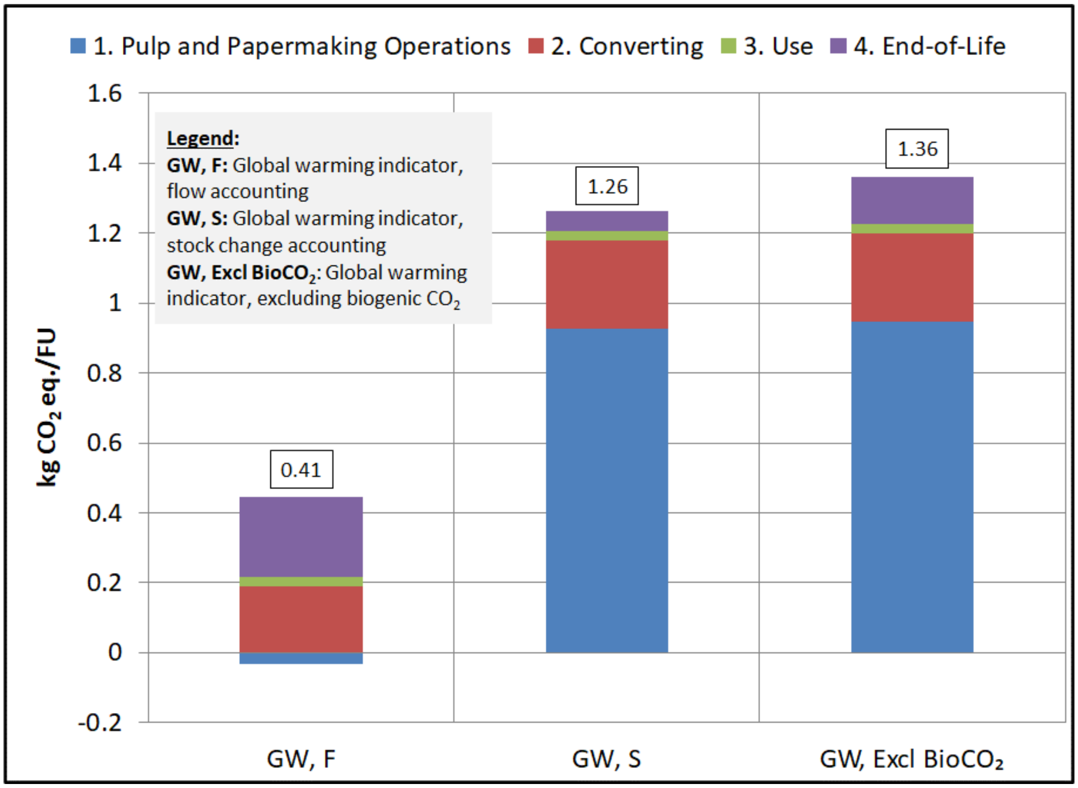

Figure 3. Effect of the Selection of the Indicator on the Observed Global Warming Results

Analyses also show that the global warming indicator results are somewhat affected by the board mix (i.e., the ratio of 100%-recycled linerboard, all other linerboard, 100%-recycled medium, and all other medium), the quantity of energy used at converting facilities and the recovery rate. Finally, somewhat different results are obtained when using the CML and TRACI methods for the eutrophication indicator, mainly because these two methods give priority to different substances released to the environment.

TS.4.4 2020 vs. 2014, 2010, and 2006 Results

One objective of this study was to compare the corrugated life cycle environmental performance in 2020 to that in 2014, 2010, and 2006 to document any changes. Table 2 presents an overview of the factors with an effect on the year-to-year comparison.[1]

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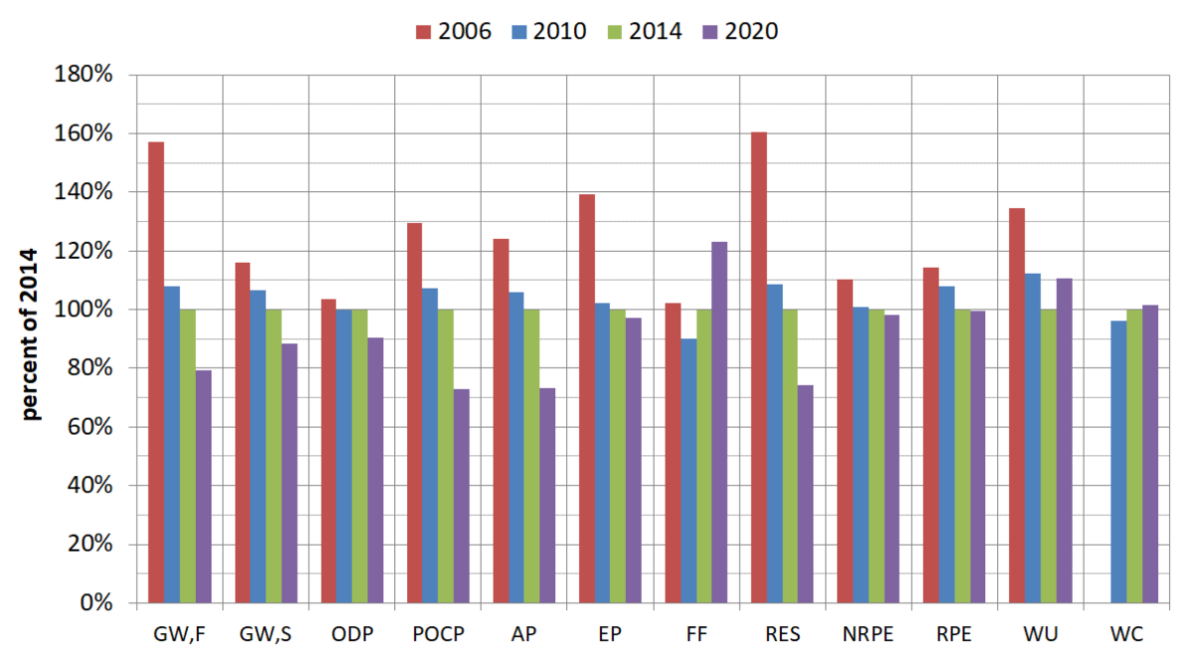
[1] The results published in this report for 2006, 2010, and 2014 vary slightly compared to those published in the 2020 report, although the general findings remain unchanged. There are a few reasons for this. First, a calculation error slightly affecting the board mix was found in the original study for 2010 and was corrected in the 2014 report. Second, some of the data source and impact assessment methodologies have been updated. Third, data collection for chemical usage at containerboard mills was streamlined. As a consequence, the 2006 and 2010 datasets were recalculated.

Table 2. Main Drivers for Change in Environmental Performance between 2006, 2010, 2014, and 2020

Model parameter	2006	2010	2014	2020	Expected effect on the results
Recovery rate	72%	85%	89.5%	90.5%	Increasing the recovery rate decreases the quantity of product going to landfill within the system boundaries with the primary effect of reducing GHG releases.
Utilization rate of recovered fiber (kg/kg CBD)	0.42*	0.46*	0.52*	0.56*	The main anticipated effects of increasing the percent board made from recycled fiber, and more specifically increasing the utilization rate, are to reduce the quantity of carbon removal in the system (sequestration), to reduce total energy use at containerboard mills (and more specifically energy from renewable sources,) and to reduce water use.
Board from 100%-recycled fibers	22.3%	26.6%	30.5%	31.8%	
Carbon removal (kg CO_2 eq./kg CP)	-2.8	-2.6	-2.4	-2.1	Lower carbon removal increases the total reported global warming results.
Total energy used by containerboard mills (MJ HHV/kg CP)	23.8	23.4	22.1	21.1	Less energy means lower emissions of GHGs and other air releases.
Share of natural gas in containerboard fossil fuels mix excluding purchased energy	46%	54%	73%	94%	More natural gas in the fuel mix generally results in lower releases of several air pollutants. However, natural gas contributes more towards the fossil fuel depletion indicator (MJ surplus) than other fossil fuels because it is harder to extract.
Total energy used at converting (MJ/kg CP)	2.1	1.9	1.9	1.7	Less total energy used means lower emissions of GHGs and other air releases. It also means lower total non-renewable energy demand.
Natural gas used at converting (MJ HHV/kg CP)	0.82	1.03	1.09	1.14	More natural gas in the fuel mix generally results in lower releases of several air pollutants. However, natural gas contributes more towards the fossil fuel depletion indicator (MJ surplus) than other fossil fuels because it is harder to extract.

NOTE: CBD is for containerboard and CP is for corrugated product.
*Numbers are different than those reported by AF&PA. AF&PA numbers include containerboard that is exported. These numbers have been corrected to exclude exports.

Figure 4 compares the impact scores obtained for 2020 with those obtained for 2014, 2010, and 2006. Changes of less than 10% are not considered meaningful (Franklin Associates 2004). From 2014 to 2020 the environmental performance generally improved. More details regarding the different indicators are provided below.



Indicator		Unit	2006	2010	2014	2020	% change 2020-2014	% change 2020-2010	% change 2020-2006
Global warming, flow accounting	GW,F	kg CO_2 eq.	0.82	0.56	0.52	0.41	-20.5%	-26.4%	-49.5%
Global warming, stock accounting	GW,S	kg CO_2 eq.	N/Av.	1.53	1.43	1.27	-11.7%	-17.2%	-23.8%
Ozone depletion	ODP	kg CFC11 eq.	7.1E-08	6.9E-08	6.9E-08	6.2E-08	-9.7%	-9.5%	-12.7%
Photo-chemical oxidation (smog)	POCP	kg O_3 eq.	0.16	0.13	0.12	0.09	-27.0%	-32.0%	-43.6%
Acidification	AP	kg SO_2 eq.	0.015	0.013	0.012	0.009	-26.7%	-30.8%	-41.0%
Eutrophication	EP	kg N eq.	1.3E-03	9.8E-04	9.5E-04	9.3E-04	-2.8%	-5.0%	-30.3%
Respiratory inorganics	RES	kg PM2.5 eq.	1.6E-03	1.1E-03	9.7E-04	7.2E-04	-25.7%	36.6%	-53.7%
Fossil fuel depletion	FF	MJ Surplus	1.80	1.59	1.76	2.17	23.2%	-31.5%	20.6%
Non-renewable primary energy demand	NRPE	MJ	20.5	18.72	18.59	18.27	-1.7%	-2.4%	-10.9%
Renewable primary energy demand	RPE	MJ	11.1	10.5	9.73	9.69	-0.4%	-7.7%	-13.0%
Water use	WU	kg	52.8	44.04	39.24	43.37	10.5%	-1.5%	-17.9%
Water consumption	WC	kg	N/Av.	10.02	10.43	10.59	1.5%	-26.4%	N/Av.

Figure 4. Comparing the Life Cycle Environmental Performance in 2020, 2014, 2010, and 2006

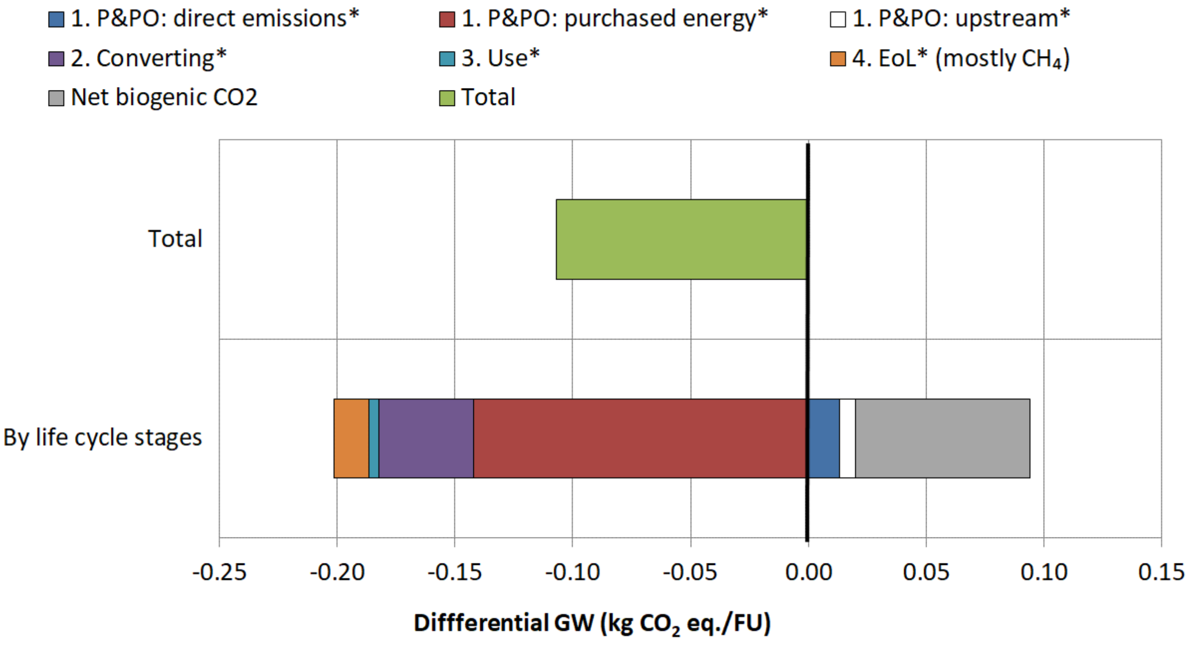
Between 2014 and 2020, the global warming indicator result decreased by 20.5% while using flow accounting (GW,F) and by 11.7% while using stock change accounting (GW,S). Figure 5 provides insight into the different parameters that affected the difference between the two years for flow accounting.

GHG emissions were reduced in some respects:

- There was a significant reduction (38%) in GHG emissions associated with purchased energy (both for pulp and paper making and for converting) due both to a reduction in purchased energy and increased greening of the grid;
- End-of-life emissions were reduced due to slight increase in recovery rate.

GHG emissions were increased in some other respects:

- The net emissions of biogenic CO_2 emissions increased.
- There was a modest increase in direct GHG emissions at pulp and paper mills, mainly because of more energy generated on-site compared to purchased.



*In this figure, P&PO means pulp and papermaking operations. The pulp and paper making life cycle stage was separated in direct emissions from pulp and paper mills (e.g., fuel combustion at containerboard mill), emissions from pulp and paper mills purchased energy, and other upstream emissions (e.g., from producing the chemicals/fuels needed in pulp and papermaking). Emissions from the four life cycle stages exclude biogenic CO_2, for which a net value is presented separately.

Figure 5. Factors Contributing to Difference in GHG Emissions between 2020 and 2014

The respiratory effects (particulates) indicator result was reduced by 26% between 2014 and 2020 mainly due to reduction of emissions of SO_2 and particulates from containerboard mills, primarily as a result of more natural gas in the fuel mix and less combustion of other fossil fuels.

There was a 10.5% increase in water use between 2014 and 2020. The increase in reported water use occurred mainly in the pulp and papermaking operations life cycle stage which is driven mostly by the change in mills participating in the 2014 and 2020 studies. Mills that participated in 2020 but not 2014 had higher water use intensity than average. If all of the mills that participated in 2020 had participated in 2014 and all of the mills that participated in 2014 had participated in 2020 there would have been a 1% decrease in water use at containerboard mills. Water consumption remained relatively stable.

Between 2014 and 2020, the impact score for fossil fuel depletion increased by 23%, which is considered to be meaningful. The main driver for this is increased consumption of natural gas in the life cycle of the product. Total renewable energy and non-renewable energy remained approximately stable.

There was no meaningful change in the ozone depletion and eutrophication indicators. The smog and acidification result showed higher reductions of 27% and 26.7%, respectively, between 2014 and 2020.

Sensitivity analyses showed that results of the comparison were generally robust. However, the global warming indicator results are sensitive to the relative contribution of the different board types in the industry-average board mix.

TS.4.5 Comparison of 100%-Recycled to Industry-Average

The environmental performance of the 100%-recycled content product relative to that of the industry-average recycled content product was derived using two allocation methods for recycling: the Number of Uses (NOU) Method and the Closed-Loop Approximation with Cut-Off (cut-off) Method. Table 3 presents the main drivers for differences in environmental performance between the two products.

Table 3. Main Drivers for Differences in Environmental Performance between the Industry-Average and 100%-Recycled Products

Model parameter	2020 Industry-Average	2020 100%-Recycled	Expected effect on the results
Utilization rate of recovered fiber (kg/kg CBD)	0.56	1.00	The main anticipated effects of increasing the percent board manufactured with recycled fiber, and more specifically increasing the recovered fiber utilization rate, are to reduce the quantity of carbon removal in the system (sequestration), reduce the total energy use at containerboard mills (more specifically, energy from renewable sources), and reduce water use.
Carbon removal (kg CO_2 eq./kg CP)	-2.4	-0.35	Higher carbon removal reduces the total reported global warming results.
Total fossil fuels used at containerboard mills (MJ HHV/kg CP)	7.24	6.41	Less fossil fuel usage means lower emissions of GHGs and other air releases. It also means lower total non-renewable energy demand.
Total biomass fuels (MJ HHV/kg CP)	11.8	0.58	Biomass fuels produce greater air emissions than natural gas.
Net fresh fiber production load transfer (applicable only to the NOU Method)	26%†	≈14%‡	Exporting/importing fresh fiber environmental load means exporting/importing environmental impacts (e.g., related to energy production) and benefits (e.g., carbon removal) of producing fresh fiber material.

NOTES: Unless otherwise specified, numbers presented in the table do not account for fresh fiber production load transfer applied with the NOU Method. CBD is for containerboard and CP is for corrugated product.
†Meaning that, when accounting for the net generation/use of recovered fiber, 26% of the environmental load from producing fresh fibers in the industry-average is exported to subsequent uses of the fiber. ‡Meaning that, for each kg of recovered fiber (mainly OCC) used in the 100%-recycled product, the environmental load equivalent of producing 0.15 kg of fresh fibers is imported within the system boundaries.

Number of Uses (NOU) Method

The environmental indicator results for the 100%-recycled product relative to those for the industry-average product obtained using the Number of Uses Method are presented in Figure 6. The following observations can be made from this figure:

- Using the NOU Method, the industry-average product results in lower environmental impact scores for the global warming, ozone depletion, smog, acidification, respiratory effects (particulates), fossil fuel depletion, non-renewable energy demand, and water consumption indicators.
- Using the NOU Method, the 100%-recycled product results in lower environmental impact scores for the renewable energy demand and water use indicators.
- Using the NOU Method, there is no significant difference between the industry-average and 100%-recycled products for the eutrophication indicator.

Sensitivity analyses other than the allocation method for recycling were undertaken to test the robustness of the comparison results. The analyses indicated that the results are relatively robust.

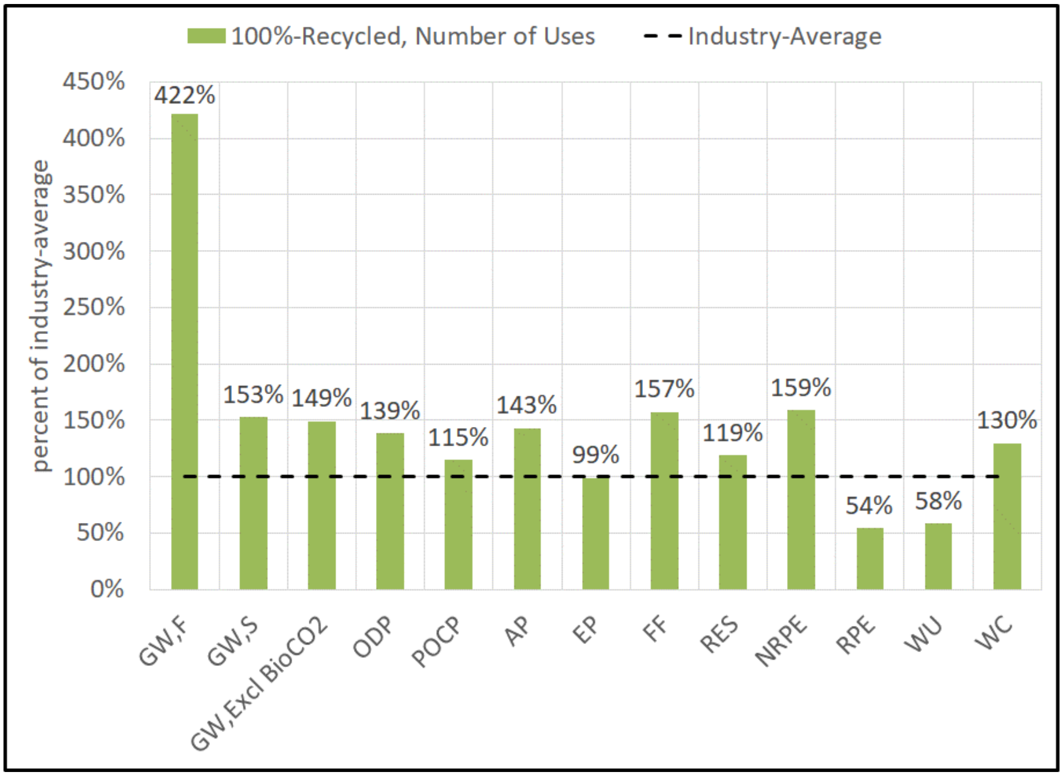


Figure 6. Impact Scores for the 100%-Recycled Product Relative to that of the Industry-Average Product (Number of Uses Method)

Closed-Loop Approximation with Cut-Off Method

The environmental indicator results for the 100%-recycled product relative to those for the industry-average product obtained using the Closed-Loop Approximation with Cut-Off (Cut-Off) Method are presented in Figure 7. The following observations can be made from this figure:

- Using the Cut-Off Method, the industry-average product results in lower environmental impact scores for the global warming (flow accounting approach) indicator.
- Using the Cut-Off Method, the 100%-recycled product results in lower environmental impact scores for ozone depletion, smog, acidification, eutrophication, respiratory inorganic, renewable energy demand, and water use indicators.
- Using the Cut-Off Method, there is no significant difference between the industry-average and 100%-recycled products for the global warming (stock change accounting), fuel depletion, non-renewable energy demand, and water consumption indicators.

Sensitivity analyses other than the allocation method for recycling were undertaken to test the robustness of the comparison results. The analyses indicated that the results are relatively robust. One exception is worth mentioning. The results for the global warming indicator are very sensitive to the selection of the accounting approach for biogenic CO_2. On one hand, the industry-average product performs significantly better than the 100%-recycled product when using the flow accounting approach. On the other hand, the difference is not significant when applying the stock change accounting method or when ignoring the emissions of biogenic CO_2. It should be noted that greenhouse gas emissions from land-use change are assumed null (see ISO 21930:2017, 7.2.11Greenhouse gas emissions from land-use change).

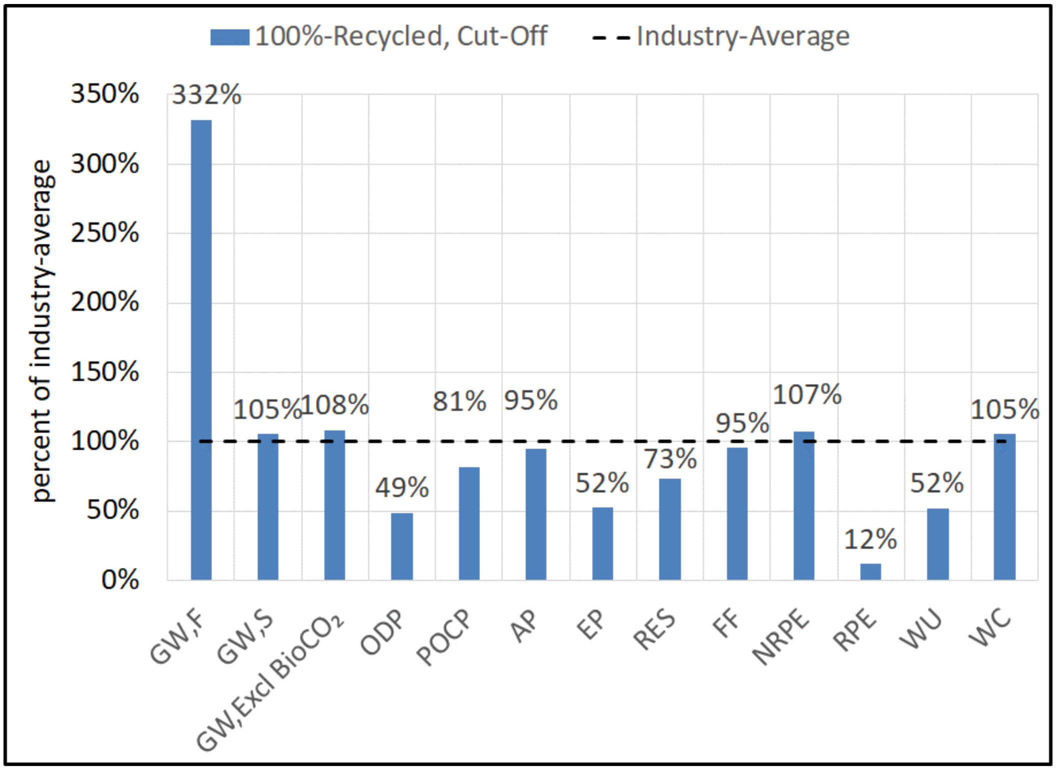


Figure 7. Impact Scores for the 100%-Recycled Product Relative to that of the Industry-Average Product (Closed-Loop Approximation w/ Cut-Off Method)

TS.4.6 Cradle-to-Gate Carbon Footprint Results

Table 4 presents the cradle-to-gate carbon footprint results for 1 kg of containerboard and 1 kg of corrugated product.

Table 4. Cradle-to-Gate Carbon Footprint

Product	**Flow accounting**				**Stock change accounting**	**Excluding biogenic CO_2**[a, b]
	Non-biogenic CO_2 GHGs[a]	**Biogenic CO_2**	**Biogenic removal**	**Net**		
	kg CO_2 eq./kg					
Industry-Average containerboard	0.87	0.93	-1.83	-0.029	0.85	0.87
Industry-Average corrugated product	1.21	1.02	-2.07	0.16	1.18	1.20
100% Recycled[c] containerboard	0.93	0.075	-0.084	0.92	0.90	0.92
100%-Recycled[c] corrugated product	1.27	0.084	0.16	1.20	1.24	1.26

[a] Refers to fossil GHGs and other non-CO_2 biogenic GHGs. [b] Value typically needed for "purchased goods and services" in GHG reporting and needed for third-party Environmental Product Declarations (EPDs). [c] Cut-off method. NOTE: For flow accounting, the GWP of CH_4 is 29.8 kg CO_2 eq./kg. For stock change accounting and accounting that excludes biogenic CO_2, the GWP of CH_4 is 27 kg CO_2 eq./kg.

TS5. Conclusions

This study represents a comprehensive LCA of the 2020 U.S. industry-average corrugated product. The main conclusions that can be drawn from the study include the following:

Pulp and papermaking production (containerboard) is the main driver of the life cycle environmental performance. For all impact categories, material and energy flows from paper mills dominate the results (positively or negatively). Environmental impacts are dominated by energy demands at the mill. Bio-based energy (e.g., hog-fuel, liquor, etc.) substantially reduces the global warming contribution from mills. Converting facilities also contribute relatively significantly to most impact categories.

End-of-Life is only significant with respect to the global warming indicator results. Other life-cycle impact indicators show little or no response from the end-of-life stage. The global warming observed at end-of-life is mainly due to methane released from landfill operations. Sensitivity analyses clearly showed that increasing the recovery rate has the potential to improve overall environmental performance.

The global warming indicator results are highly dependent on the accounting method for biogenic CO_2. Two different accounting approaches can be used to compute the results for the global warming indicator: flow accounting, which was the main method employed in this study, and stock accounting, which was examined using a sensitivity analysis. Flow accounting is the accounting method most frequently used in LCA studies. Stock change accounting is primarily used in national inventories. Another approach sometimes used in LCA is simply ignoring biogenic CO_2 when calculating the global warming indicator results to get an understanding of how non-biogenic CO_2 GHG emissions contribute to the global warming indicator. Note that this latter approach ignores any removal/storage of biogenic carbon. The pulp and papermaking operations life cycle went from being an insignificant contributor to global warming when applying the flow accounting approach to a very significant contributor when applying the stock change method or ignoring biogenic CO_2. When applying the stock change accounting approach or ignoring biogenic CO_2, the contribution of end-of-life to the overall global warming results was reduced compared to when applying the flow accounting method.

Overall, the life cycle environmental performance of the containerboard sector was essentially improved between 2014 and 2020. Significant improvements were observed for the global warming, smog, acidification, and respiratory effects (particulates) indicators. However, there was an increasing trend observed in fossil fuel depletion due to higher share of natural gas in the mix which is harder to extract than other fossil fuels. That said, total energy use (irrespective of the fuel) was relatively stable.

The results of comparisons of the industry-average product to 100%-recycled product varied by indicator, with some results being strongly dependent on the allocation method chosen for recycling. In summary, the industry-average indicator results were lower for the global warming indicator using flow accounting method, regardless of the allocation method used. The results for fossil fuel depletion, non-renewable energy, and water consumption indicators obtained with the Cut-Off Method showed that the difference between the two products was not significant. Results also suggest that the 100%-recycled product generates lower emissions of eutrophying substances and uses less water and renewable energy than the industry-average, although for the eutrophication indicator the results obtained with the Number of Uses Method showed that the difference between the two products was not significant. The results for the other environmental indicators (i.e., ozone depletion, smog, acidification, respiratory effects) depend on the allocation method.

TS6. Limitations and Recommendations

With regards to the 2020 LCA results the main limitations are as follows.

- 100%-recycled products were relatively less well represented in the data collected, especially 100%-recycled corrugated medium. Note that, when developing the industry-average, the actual board mix was used, eliminating the bias due to under-represented board types in the industry-average. In addition, no industry survey can ever pull in 100% of the operating facilities, and that anomalies across any sector for which an LCA is being conducted may be either obscured or magnified due to the universe of mills that provide survey responses. Future LCAs should focus on improving the representation of 100% recycled corrugating medium while addressing potential biases by including a bigger sample of facilities.
- There were small discrepancies in mass/carbon balances. Carbon balances were adjusted to be conservative.
- The data collection was performed in a way that ensured that any flow contributing to more than 1% of the mass inputs of those processes was included, except for chemicals. Knowledge gained during the previous LCA efforts, in terms of the point after which additional data do not add measurable benefit to the robustness of the final LCA results, justified the assessment to include only those chemicals contributing more than 10% of the total dry mass of chemicals used in each containerboard component. In this manner, no chemicals with significant individual contribution to any environmental indicator (i.e., > 5%) would be ignored. In addition, the mills were asked to report the total mass of "other fillers", which would account for a large proportion of the missing chemicals. Future LCAs should revisit the list of chemicals included in data collection efforts to ensure there are no new chemicals used by the industry that should not be ignored.

In terms of the yearly comparisons, the limitations described above also apply. The 2020 data were scaled to match the board mix actually produced, as was done previously for the 2014 and 2010 data. This was not possible using 2006 data because of the way the data were collected at that time.

In terms of the 100%-Recycled/industry-average comparison, the limitations described above also apply. In addition, differences in board types' representativeness were also identified as a potential shortcoming. The general conclusions of the comparison were shown not to be significantly affected (less than 10% difference) by this limitation

1. INTRODUCTION

The main objective of this LCA was to generate high-quality, up-to-date data on the potential environmental impacts of corrugated packaging. With such an LCA study, the Corrugated Packaging Alliance (CPA) and its constituent associations can assist other organizations in understanding and communicating the environmental footprint and benefits associated with using corrugated packaging rather than other materials. At the same time, the study can help describe the potential environmental impacts of different life cycle stages in relation to overall environmental performance and the potential environmental benefits of process improvements. The study evaluated the environmental performance of an industry-average corrugated product throughout its entire life cycle. The study is intended to provide useful perspective for different stakeholder groups.

The study was sponsored by Corrugated Packaging Alliance (CPA), a joint venture of the American Forest & Paper Association (AF&PA), Fibre Box Association (FBA), the Independent Packaging Association (AICC) and TAPPI. The study was undertaken through a collaboration of the National Council for Air and Stream Improvement (NCASI) and Anthesis.

The study was based on information from 51 containerboard mills representing 69% of 2020 U.S. containerboard production and 402 converting facilities representing 57% of overall containerboard converting production volume for 2020.

Life Cycle Assessment (LCA) is a standardized, scientific method for systematic analysis of flows (e.g., mass and energy) associated with the life cycle of a specific product, technology, service, or manufacturing process system. The approach in principle aims at a holistic and comprehensive analysis of the above items, incorporating raw materials acquisition, manufacturing, use, and end-of-life (EoL) management. According to the International Organization for Standardization (ISO) 14040/44 Standards (ISO 2006a, 2006b), an LCA study consists of four phases: (1) goal and scope (framework and objective of the study); (2) Life Cycle Inventory (input/output analysis of mass and energy flows from operations along the product's value chain); (3) Life Cycle Impact Assessment (evaluation of environmental relevance, e.g., global warming potential); and (4) interpretation (e.g., optimization potential).

The goal and scope stage outlines the rationale of the study, anticipated use of study results, boundary conditions, data requirements and assumptions for analyzing the product system under consideration, and other related technical specifications for the study. The goal of the study is defined based upon specific questions that the study seeks to answer, the target audience and stakeholders involved, and the intended use for the study's results. The scope of the study defines the system's boundary in terms of technological, geographical, and temporal coverage, the attributes of the product system, and the level of detail and complexity addressed.

The Life Cycle Inventory (LCI) is merely a list of input and output flows with no associated environmental relevance. LCA characterizes the flows and describes their potential effects on the environment. The Inventory stage qualitatively and quantitatively documents the materials and energy used (the "inputs") as well as the products, by-products, and environmental releases in terms of emissions to the environment and wastes to be treated (the "outputs") for the product system being studied. The LCI data can be used on its own to understand total emissions, wastes and resource use associated with the material or product being studied or used directly to improve production or product performance. Alternatively, LCI data can be further analyzed and interpreted to provide insights into the potential environmental impacts from the system (Life Cycle Impact Assessment and Interpretation, LCIA).

To respond to increasing interest among product manufacturers and consumer retail markets in selecting more sustainable packaging options, CPA engaged NCASI to update the results of an LCA they published in 2017 that relied primarily on 2014 data (https://fibrebox.wpenginepowered.com/wp-content/uploads/PDFs/LCA/2014_Corrugated_Industry_LCA_Full_Report.pdf) to the most recent available data (i.e., 2020 data). In updating this previous study, NCASI updated these data and made minor changes to the methodology where appropriate and corrected minor calculation errors in the previous data.

The current study has benefited from the cooperation and support of many manufacturers in this sector who contributed their data for use as primary data sources in this report.

2. GOAL OF THE STUDY

The ISO 14044 Standard (ISO 2006b) specifies that "The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application" and that "Due to the iterative nature of LCA, the scope may have to be refined during the study."

The goal of this study was to update the LCA published in 2017 using 2014 data for a 1 kg U.S. industry-average corrugated product, with 2020 data. More specifically the objectives of the study were as follows:

1. To educate customers and stakeholders about the environmental attributes of the industry's corrugated products produced in 2020:
    a. To identify which life cycle stages contribute the most to these attributes.
    b. To provide a basis for documenting improvements in these attributes over time.
    c. To provide information to facilitate any future comparative study.
    d. To update the data in the U.S. LCI database.
2. To contrast, to the extent possible, the updated results for 2020 with the results of 2006, 2010, and 2014 LCA studies.
3. To present the environmental performance of a corrugated product made of 100%-recycled fiber relative to that of the industry-average recycled content.

The primary audience for this study is CPA, its member companies that produce linerboard, medium and boxes, and their customers. The results will also be disclosed to the public. The study has been conducted according to the requirements of the ISO 14044 Standard (ISO 2006b) and was subjected to a third-party critical review (critical review by an expert interested party).

When results of the LCA are to be communicated to any third party (i.e., interested party other than the commissioner or the practitioner of the study), regardless of the form of communication, a third-party report shall be prepared, according to the ISO 14044 Standard. The third-party report constitutes a reference document and shall be made available to any third party to whom the communication is made. It is the intent of this report to act as a third-party report.

It is important to note that any environmental claim regarding the the comparison of 100%-recycled product to industry-average product (objective #3 above) is a comparative assertion as defined in the ISO 14044 Standard. The results presented in this report have been peer reviewed to meet the requirements of the Standard.

3. SCOPE OF THE STUDY

The following section describes the general scope of the project to achieve the stated goal. This includes identification of the average corrugated product to be assessed, the boundary of the study, functional unit, data quality requirements, etc. More information on the methodology employed can be found in Sections 4 and 5.

3.1 Product under Study

3.1.1 2020 Industry-Average Product

The main product being studied is the U.S.-average corrugated product (e.g., corrugated box) manufactured in 2020. Corrugated products are made of corrugated board (combined board). Corrugated board is the structure formed by bonding one or more sheets of fluted corrugating medium to one or more flat facings of linerboard. When this consists of a single facing, it is referred to as single-face board. If bonded on both sides, it becomes double-faced or single wall corrugated board. In addition to singlewall board, doublewall and triplewall corrugated boards are also produced (see Figure 8).

As shown in Table 5, data were collected for different types of board. Because of the relatively low survey response rate compared to previous years, the board mix represented in the dataset was not fully representative of containerboard produced and used in the U.S. For this reason, the data were scaled to be more representative. In general, recycled board was under-represented in the collected information.

Table 5. Mix of Boards in 2020 U.S.-Average Containerboard

Board type	As collected	Actual (as modeled)*
100%-recycled linerboard	16.6%	15.8%
All other linerboard	59.9%	50.1%
Total linerboard	***76.6%***	***65.9%***
100%-recycled corrugating medium	6.6%	16.0%
All other corrugating medium	16.8%	18.1%
Total corrugating medium	***23.4%***	***34.1%***

**Estimated based on U.S. actual production excluding imports.*

Typically, corrugated products are used as secondary packaging[2] of products for shipping. The average basis weight of the U.S. industry mix is 123.4 lb/thousand square feet (msf, 0.603 kg/m^2) and consists of approximately 0.6% singleface, 90.9% singlewall, 8.0% doublewall, and 0.5% triplewall.

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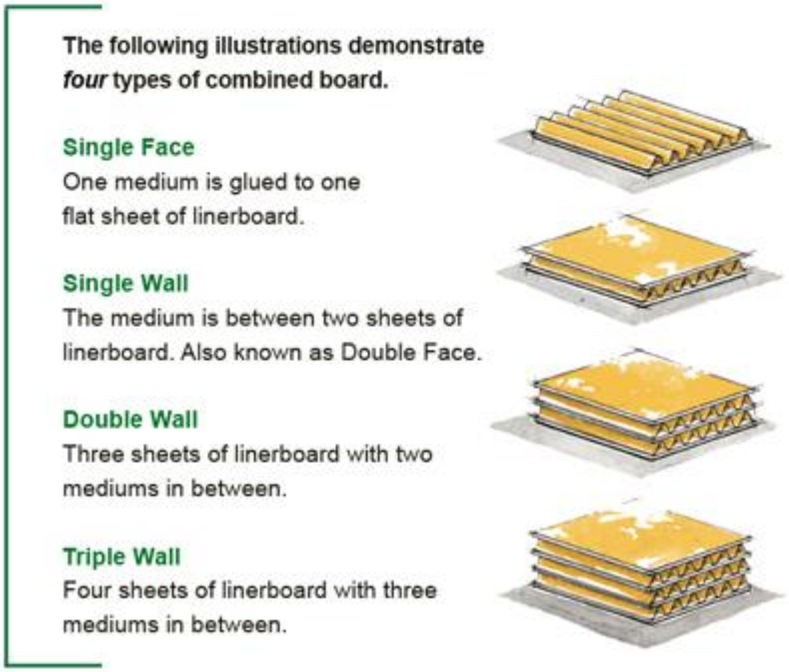
[2] It is sometimes convenient to categorize packages by layer or function: "primary", "secondary", etc. Primary packaging is the material that first envelops the product and holds it. Secondary packaging is outside the primary packaging, perhaps used to group primary packages together.



The following illustrations demonstrate *four* types of combined board.

Single Face
One medium is glued to one flat sheet of linerboard.

Single Wall
The medium is between two sheets of linerboard. Also known as Double Face.

Double Wall
Three sheets of linerboard with two mediums in between.

Triple Wall
Four sheets of linerboard with three mediums in between.

Figure 8. Various Structure of Corrugated Board
[from www.corrugated.org]

3.1.2 Comparison of 2020,. 2014, 2010 and 2006 Industry-Average Products

As mentioned above, the 2020 data were scaled to match the board mix actually produced, as was done previously for the 2014 and 2010 data. This was not possible using 2006 data because of the way the data were collected at that time. The board mixes in 2006, 2010, 2014, and 2020 are presented in Table 6. As highlighted in light gray in the table, because the utilization rate of recovered fiber was likely to have a significant effect on the results (see more details in Section 4.2.1.3), it was decided to compare the yearly environmental performance based on the "2006, as collected", "2010, actual", “2014 actual”, and “2020, actual” datasets. However, given that this implies doing a comparison based on slightly different methodologies, the “2006, as collected” dataset was also compared to the “2010, as collected”, “2014, as collected”, and “2020, as collected”, as this was performed in previous reports (NCASI 2014).

Table 6. Mix of Boards in U.S.-Average Containerboard (2006, 2010, 2014, and 2020)

Board type	**2006**	**2010**	**2014**	**2020**
	Actual	**Actual***	**Actual**	**Actual**
100%-recycled linerboard	10.0%	13.5%	16.1%	15.8%
All other linerboard	57.3%	55.3%	50.7%	50.1%
Total linerboard	***67.3%***	***68.8%***	***66.8%***	***65.9%***
100%-recycled corrugating medium	12.3%	13.1%	14.4%	16.0%
All other corrugating medium	20.4%	18.1%	18.8%	18.1%
Total corrugating medium	***32.7%***	***31.2%***	***33.2%***	***34.1%***

More details on the methodology employed to compare 2006, 2010, 2014, and 2020 environmental performance can be found in Appendix B.

The average basis weight of industry-average product was:

- 138.6 lb/thousand square feet (msf, 0.677 kg/m^2) in 2006;
- 131.9 lb/thousand square feet (msf, 0.644 kg/m^2) in 2010, or 4.8% lower than in 2006;
- 131.6 lb/thousand square feet (msf, 0.643 kg/m^2) in 2014, or 5.1% lower than in 2006 and 0.2% lower than in 2010;
- 123.4 lb/thousand square feet (msf, 0.603 kg/m^2) in 2020, or 11.0% lower than in 2006, and 6.23% lower than in 2014.

This report compares the annual environmental profile of industry-average corrugated product on the basis of the same mass of product. However, reduction in basis weight in theory means that, from year to year, less product (on a mass basis) is required to perform the same function. For this reason, the effect of basis weight reduction is discussed in a sensitivity analysis.

3.1.3 100%-Recycled Product

As shown in Table 7, data were collected for different types of boards. When comparing industry-average and 100%-recycled products, the same mix of linerboard to corrugating medium was considered. It was also assumed that the average basis weight of the 100%-recycled was the same as that of the 2020 industry-average.

This means that the environmental attributes of the 100%-recycled product discussed in this report are those of a theoretical 100%-recycled product that is functionally equivalent of that of the industry-average product and do not represent the actual “industry-average” 100%-recycled produced and used in the U.S.

Table 7. Mix of Boards in 100% Recycled Containerboard

Board type	**Industry-Average as Modeled***	**100%-Recycled as Modeled***
100%-recycled linerboard	15.8%	65.9%
All other linerboard	50.1%	0%
Total linerboard	***65.9%***	***65.9%***
100%-recycled corrugating medium	16.0%	34.1%
All other corrugating medium	18.1%	0%
Total corrugating medium	***34.1%***	***34.1%***

**Estimated based on U.S. actual production excluding imports.*

3.2 Representativeness

Representativeness is an assessment of the degree to which the data reflects the true population of interest. In this study, the population of interest is plants producing containerboard and converting containerboard in the U.S. Table 8 provides information on the technology representativeness of the data collected for this study. It shows that, overall, 70% of the 2020 U.S. production of containerboard was included in the study. Board made from anything other than 100%-recycled fiber was well represented, while 100%-recycled products are relatively less well represented, especially 100%-recycled corrugated medium. Note that, when developing the industry-average, the actual board mix was used. This eliminated the bias due to under-represented board types in the industry-average. However, it was assumed that the data collected for each individual board type were representative of the average for that board type. The data collected for converting plants represented a lower proportion of the U.S. production, but it was still assumed that they were representative of the average.

No industry survey can ever pull in 100% of the operating facilities, and that anomalies across any sector for which an LCA is being conducted may be either obscured or magnified due to the universe of mills that provide survey responses.

Table 8. Estimated Technology Representativeness of Containerboard Mills and Converting Plants (2020)

Product type	Percent of U.S. Production Included*	Mills/Plants Included	Total Mills/Plants in U.S.*
100%-recycled linerboard	76%	15	36
All other linerboard	75%	27	39
100%-recycled corrugated medium	33%	10	11
All other corrugating medium	72%	17	46
Containerboard - Overall	***69%***	***51***	***77***
Corrugator plants	N/Av	264	395
Sheet feeder plants		32	64
Sheet plants		106	694
Converting - Overall	***57%*****	***402***	***1153***

**Estimated. **Percent of the containerboard produced and converted in the U.S.*

Figure 9 and Figure 10 show the geographical distribution of facilities that participated in data collection and Table 9 data on geographical coverage. Overall, the data collected for containerboard mills is representative of the geographic distribution of containerboard mills in the US. Data collected for converting facilities is representative of the actual geographical distribution.

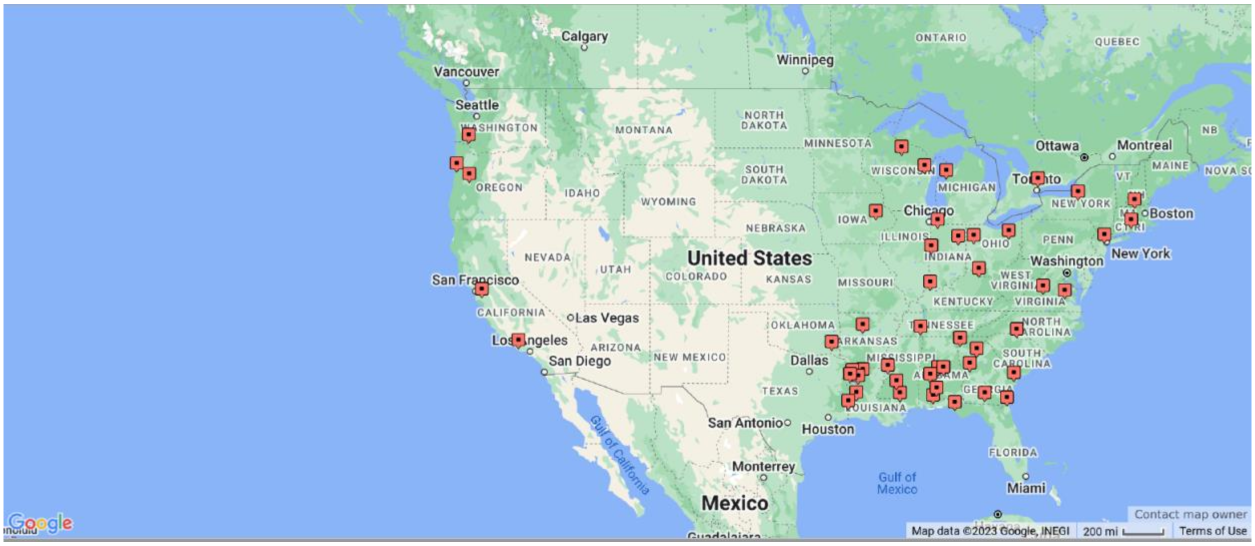


Figure 9. Geographical Distribution of the Containerboard Mills that Participated in Data Collection

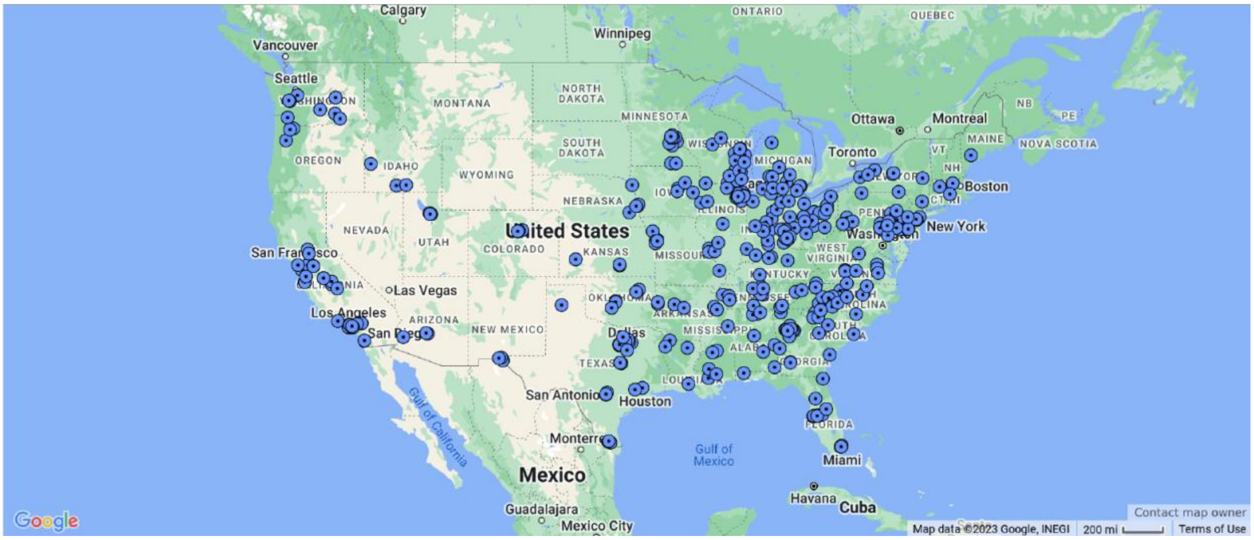


Figure 10. Geographical Distribution of the Converters that Participated in Data Collection

Table 9. Estimated Geographical Coverage of Containerboard Mills and Converting Plants (2020)

Region	Containerboard Mills Included	Total Mills in the U.S. Producing Containerboard	Converting Plants Included	Total Plants in the U.S.
Eastern	44 (86%)	64 (83%)	199 (50%)	630 (55%)
Western	7 (14%)	13 (17%)	146 (36%)	368 (32%)
Central	-	-	57 (14%)	155 (13%)

3.3 Function, Functional Unit and Reference Flows

The **function** of the product system under study is the domestic use of an average U.S.-produced corrugated product mainly used as secondary packaging of products for shipping.

The **functional unit** is defined as:

"The domestic use[3] of 1 kg of an average corrugated product produced in the U.S. in 2020."

The materials that would be enclosed within the corrugated product while the corrugated product is in use are not included in the study. Note that the function and functional unit described above are not directly intended for comparative analyses. This is because not all packaging has the same functionality at the same mass. In cases where the results would be used for comparative analyses, it should be demonstrated that the compared products perform similar functions.

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[3] The ratio of the different board types produced in the U.S. (100%-recycled linerboard, all other linerboard, 100% corrugating medium, and all other medium) was adjusted to account for exports of these respective board types. As such, the LCA results are representative of corrugated products produced and used in the U.S. rather than produced in the U.S. irrespective of where they are used.

The reference flows are thus defined as the different process outputs for the production of 1 kg of a corrugated product. Quantitative information on the reference flows is provided in the next sections.

The product system investigated delivers functions other than that of the defined functional unit. Examples include: 1) managing the wastes from other systems (through use of recovered paper), and 2) producing raw material for other systems (through recovery of old corrugated containers for subsequent recycling, turpentine production, etc.). These functions are excluded from the scope of this study through the application of appropriate allocation procedures (see Section 3.5).

3.4 System Boundary

3.4.1 Overview of the Product System

The corrugated product system was investigated in this study and is depicted in . The system boundary was set according to a cradle-to-grave approach (from raw material extraction to the final disposal of the corrugated product). Containerboard is the primary raw material in the converting process, which results in the corrugated product. The system boundary, as illustrated in Figure 9, has been separated into four life cycle stages: 1) pulp and papermaking operations, 2) converting, 3) use, and 4) end-of-life.

1) **Pulp and papermaking operations**, including forest operations, transportation of wood to chipping, transportation of recovered fiber to the facility, off-site chipping, on-site production of chips, off-site production of market pulp, production of on-site produced pulp, papermaking operations (to produce containerboard), conversion into rolls, offsite production of purchased chemicals, fuel, and energy, and supporting activities (on-site steam and power production, on-site chemical production, effluent treatment, on-site waste management, offsite effluent treatment at publicly owned treatment works (POTW), etc.).
2) **Converting** includes the activities involved in converting the linerboard and corrugating medium into corrugated packaging.
3) **Use** includes transportation to the use phase but does not include energy and resources used during the use life cycle stage.
4) **End-of-life** includes end-of-life management of the packaging product (landfilling, burning with energy recovery).

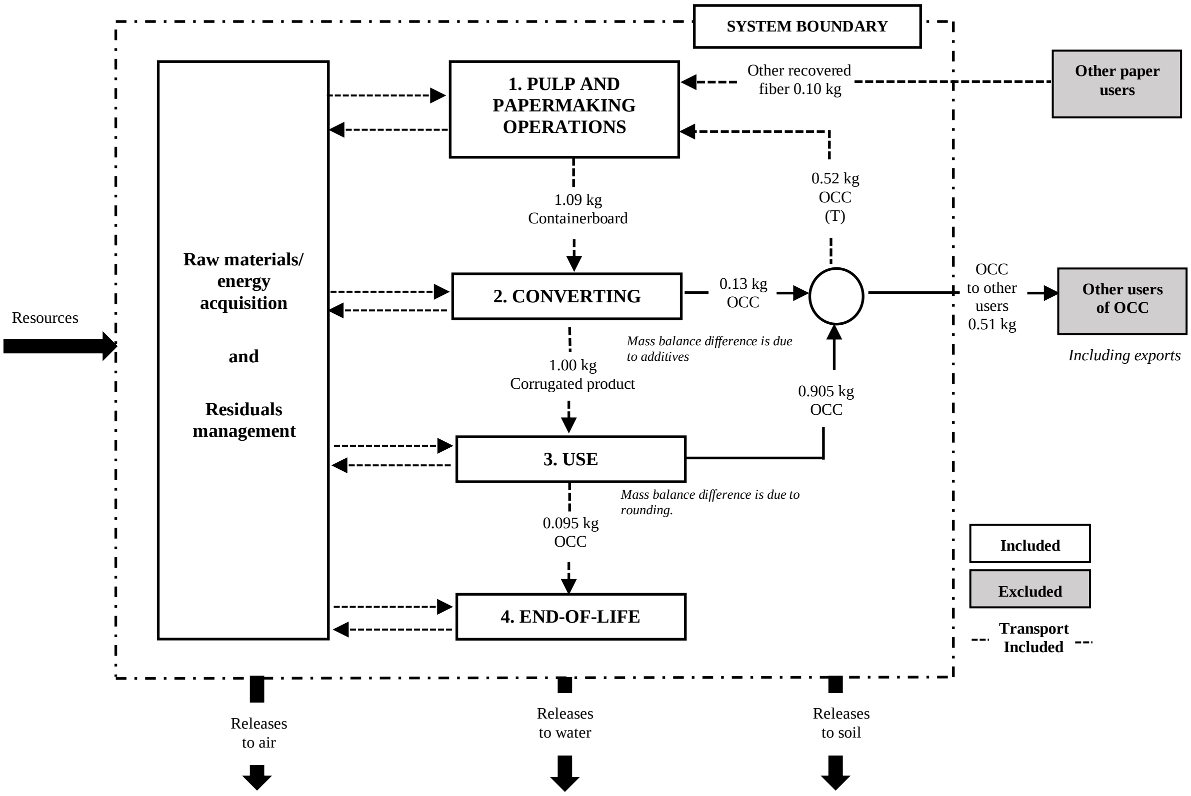

Figure 11. System Boundary for the Corrugated Product System

In addition, as shown in Figure 11, each life cycle stage comprises upstream raw material extraction and production, downstream management of residuals, and transportation between related unit processes. Transportation between two life cycle stages is included within the downstream stage. Each life cycle stage and related unit processes are discussed in detail in Section 4.2.

3.4.2 Omissions/Exclusions

The study did not include capital equipment and maintenance, maintenance and operation of support equipment, or transport of employees. In addition, the study did not include energy related to the use of the packaging product, nor that of the product packaged by it.

Other overhead functions such as HVAC and lighting were included to the extent they are considered in total mill energy usage as reported by participating companies.

3.4.3 Geographic Boundary, Temporal Boundary, and Summary of Unit Processes Included

The geographical boundary relates to various aspects in LCA, given that:

- the resources involved may come from different regions of the world;
- the infrastructure, such as transport systems, energy production (electricity grid, for example) and waste management, differ in different regions; and

- the sensitivity of the environment to various pollutants varies from one geographical area to another.

The temporal boundary of an LCA includes the period associated with the functional unit, considering the periods of production, distribution, use (lifetime), and management at the end of product life, along with the period of effect of the substances emitted to the environment. In this study, the period associated with the functional unit is the year 2020. All activities related to the production of corrugated products during this calendar year were therefore included within the temporal boundary of the system. It should be noted that some processes within this boundary can generate releases over a longer period (e.g., landfills). These delayed emissions were annualized and added to the 2020 inventory data. A life cycle impact assessment (LCIA), which is one step in an LCA, considers the full range of persistence and effect of the substances emitted into the environment and thus would capture this type of longer release. The modeling approach and time horizon for evaluation is defined by the LCIA method selected.

Boundaries are summarized in Table 10.

Table 10. Summary of Boundary Conditions

Life cycle stage and/or unit process	**Temporal boundary (Reference year is 2020)**	**Geographic boundary**	**Processes included and excluded**
Raw material and fuels extraction and production: Fiber	Annual average emissions over a growth cycle and annual average emissions for producing the logs/chips/recycled fiber	Area from which the wood and recycled fiber is obtained and transformed (may include U.S. and Canada, depending on the paper grade)	Included: thinning, harvesting, intermediary transportation[4]; Excluded: capital equipment and maintenance, human activities
Raw material and fuels extraction and production: Chemical and fuels[5]	Average annual amounts of fuels consumed and other non-fiber inputs during the reference year	Raw material and fuels assumed to be produced in North America (excluding Mexico)	Included: production of raw material and fuels required in all life cycle stages; Excluded: capital equipment and maintenance, human activities
Raw material and fuels extraction and production: Electricity[6]	Average annual amounts of electricity consumed during the reference year	Grid-specific electricity for pulp, paper, and production of final products: U.S. grid for end-of-life North American grid for others	Included: combustion and pre-combustion; Excluded: capital equipment and maintenance, human activities
Pulp and papermaking operations	Annual average emissions	All locations where pulp and containerboard are produced including: • Market pulps: U.S. and Canada • Containerboard: U.S.	Included: on-site chipping, pulping, papermaking, converting, steam production, on-site chemical production, on-site waste management, transportation from upstream life cycle stages and intermediary transportation, etc.; Excluded: capital equipment and maintenance, human activities
Converting	Annual average emissions	All locations where corrugated packaging is produced (U.S.)	Included: converting operations, transportation from paper production; Excluded: capital equipment and maintenance, human activities
Use	Time during which products are used	All locations where corrugated packaging is used (U.S.)	Included: transportation from converting plants; Excluded: capital equipment and maintenance, human activities, energy and resources for using the corrugated packaging
End-of-life	Time for maximum degradation	All locations where corrugated packaging is disposed of (U.S.)	Included: emissions from end-of-life activities, transportation from use life cycle; Excluded: capital equipment and maintenance, human activities
Off-site waste management[6]	Time for maximum degradation	All locations where waste management occurs	Included: emissions from waste management, transportation to the management site; Excluded: capital equipment and maintenance, human activities

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[4] Intermediary transportation is transportation between two unit processes within the same life cycle stage.

[5] As mentioned above, supply of raw materials and energy, as well as off-site waste management, were integrated within the life cycle stage they supply. However, they have specific boundary conditions.

3.5 Allocation Procedures

Two types of allocation issues were accounted in this study: allocation related to co-products and allocation related to recycling. More specifically, the main allocation situations that were encountered in this study were:

- sawmill co-products (lumber, chips and wood residues);
- internal allocation, i.e., containerboard mill co-products (different grades of paper produced at the same mill);
- containerboard mill by-products (e.g., turpentine and tall oil, sold energy);
- containerboard mill beneficial uses (e.g., land application of wastewater treatment plant residuals); and
- recycling (to and from the studied system).

The methods selected for the allocation situations are described and justified in the next sections.

3.5.1 General Considerations in Selecting Allocation Methods

Appendix A discusses the different options described under the ISO 14044 Standard to deal with co-products and recycling allocation. As discussed in this Appendix, ISO 14044 recommends dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes (system subdivision) or expanding the system boundary (system expansion) as the preferred options for dealing with allocation for co-products and recycling allocation situations. In the literature, there is general agreement that system subdivision applies regardless of the study objective, but that system expansion is better suited to LCAs with the objective of analyzing consequences of a change in a product system (e.g., Baumann 1996, Baumann and Tillman 2004, Ekvall 1999, Ekvall et al. 2005, Ekvall and Weidema 2004, Werner 2005a). In this study, the objective was to characterize the environmental attributes of the corrugated products and not to analyze the consequences of a change in a given product system. Hence, system subdivision was always used where possible and system expansion was never selected as a first choice.

3.5.2 Sawmill Co-Products

The data available in the U.S. LCI database for sawmill co-products were developed by CORRIM[6] (Kline 2004, Milota 2004, Milota et al. 2004, Wilson and Sakimoto 2004) using mass allocation. This choice was not modified, although using mass allocation falls within the last option for allocation under the ISO Standard. A previous study (NCASI 2010) showed that the choice of the allocation method for sawmill co-products has little effect on the cradle-to-grave results when chips are the studied product from the sawmill. For this reason, no sensitivity analysis was performed on this choice of allocation method.

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[6] The Consortium for Research on Renewable Industrial Materials (CORRIM) is a research organization that develops a scientific base of information relating to the environmental performance of wood-based building products.

3.5.2.1 Internal Allocation

A given containerboard mill can produce several paper products (containerboard products and non-containerboard products). If only some of the products from the mill are among those being studied, this requires that the environmental load[7] of the containerboard mill be partitioned (allocated) between the studied product and the other products. The first strategy used in this study to resolve this internal allocation problem was to subdivide as much as possible the containerboard mill into its various departments and to collect data specific to these departments (system subdivision) while, at the same time, minimizing the data collection burden for participating mills. More specifically, the following data were collected and used for applying system subdivision:

- mill-level releases and fuel consumption;
- quantity of each product produced in the mill;
- quantity of each fiber furnish produced at the mill and in which product it is used;
- quantity of each fiber furnish purchased by the mill and in which product it is used;
- quantity of fiber inputs (e.g., wood, recovered paper) for each of the fiber furnishes produced in the mill;
- total heat energy used by each department;
- total electricity used by each department; and
- quantity of other raw materials (e.g., chemicals, paper additives) used by each department.

However, system subdivision was not sufficient to fully resolve the internal allocation problem, and additional allocation methods were required to allocate specific fuels and releases to the various products.

Fuels were allocated using underlying physical relationships by applying, to the extent possible, the process-based hierarchy originally proposed by AF&PA (1996) and extended by NCASI for the purposes of this LCA. This hierarchy is presented in Table 11. Fuel-related releases were allocated based on fuel consumption.

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[7] In this report, an environmental load is any input flow or non-product output flow to and from a unit process or set of unit processes.

Table 11. Proposed Allocation Hierarchy for Fuels

Fuels in Order of Allocation		**Processes in Order of Allocation**	
1.	Fuels for specific usage[*]	1.	Specific usage[*]
2.	Black liquor solids, and TMP steam recovery	2.	Wood pulping and chemical recovery[†]
		3.	Bleaching of wood pulps
3.	Self-generated bark and wood wastes	4.	Paper production (wood pulps only)
4.	Purchased bark and wood wastes, fossil fuels, and steam	5.	Recovered fiber pulping, bleaching, and paper production

[*] *For instance, the fuels allocated to on-site electricity production should reflect the steam that goes through the turbine. If all boilers are connected to the turbine, then a proportional fuel mix should be allocated to electricity production. If only recovery boilers are connected to the turbine, then only black liquor solids should be allocated to electricity production.* [†] *For kraft pulping, combining pulping and chemical recovery into a single unit process will often facilitate the allocation.*

Purchased electricity was allocated based on each department’s consumption.

Non-toxic (as defined by the U.S. Toxics Release Inventory), non-fuel-related environmental releases for which data are collected at the mill level were allocated using a modified mass allocation method developed by NCASI, documented in Appendix E. This NCASI method is a hybrid of underlying physical relationships and other relationships in the ISO hierarchy of approaches.

Toxic releases (as defined by the U.S. Toxics Release Inventory) to air, water, and soil were modeled.

Given that this approach is as close as possible to avoiding allocation and applying underlying physical relationships under the ISO hierarchy of approaches, no sensitivity analysis was performed.

3.5.2.2 Containerboard Mill’s Co-Products

There are two main co-products that required allocation: turpentine and tall oil, and sold energy.

The quantity and value to the industry of turpentine and tall oil are usually small compared to those of containerboard products. For this reason, different allocation procedures are unlikely to have a significant effect on the results and thus, mass allocation was used (other relationship in the ISO hierarchy) and no sensitivity analysis was performed.

Fuels and combustion-related emissions were allocated to either energy used in the mill and/or energy sold, based on energy content and the hierarchy discussed in Table 11. System expansion was used as a sensitivity analysis because it is used extensively for electricity consumption in both accounting and change-oriented LCAs.

3.5.2.3 Beneficial Uses

Solid residuals from containerboard manufacturing are commonly used for beneficial uses such as agricultural or silvicultural land application, construction materials, chemical feedstock, or fuels. Another example of beneficial use of waste is burning of used products at the end of life, with energy recovery. The functions related to these beneficial uses are outside the scope of this LCA, and thus an allocation procedure must be applied. As a conservative simplification, the residuals, even if they are beneficially used, were not considered as co-products but as waste and no allocation was required.

3.5.2.4 Recycling

As shown in Figure 12, there are some recycling-related activities that occur in the investigated product system:

- converting wastes that are recycled within containerboard production;
- old corrugated containers that are recycled within containerboard production;
- imports of recovered fiber from other product systems (mainly mixed papers); and
- exports of recovered fiber to other product systems (mainly U.S. paperboard production and foreign exports).

The ISO 14044 Standard and ISO 14049 technical report distinguish between two types of product systems: closed-loop product systems and open-loop product systems. The investigated product system is a hybrid of a closed-loop and open-loop product system because both closed-loop and open-loop recycling occur in the product system. Recycling of converting wastes and old corrugated containers within containerboard production can be described as closed-loop recycling, while imports and exports of recovered fiber to and from the investigated product system are cases of open-loop recycling. The ISO Standard specifies that a closed-loop procedure (i.e., no allocation needed) applies to closed-loop systems and that an open-loop procedure (i.e., some sort of allocation method needed) applies to open-loop systems, meaning that an allocation method should be selected for the “open-loop” component of the product system investigated.

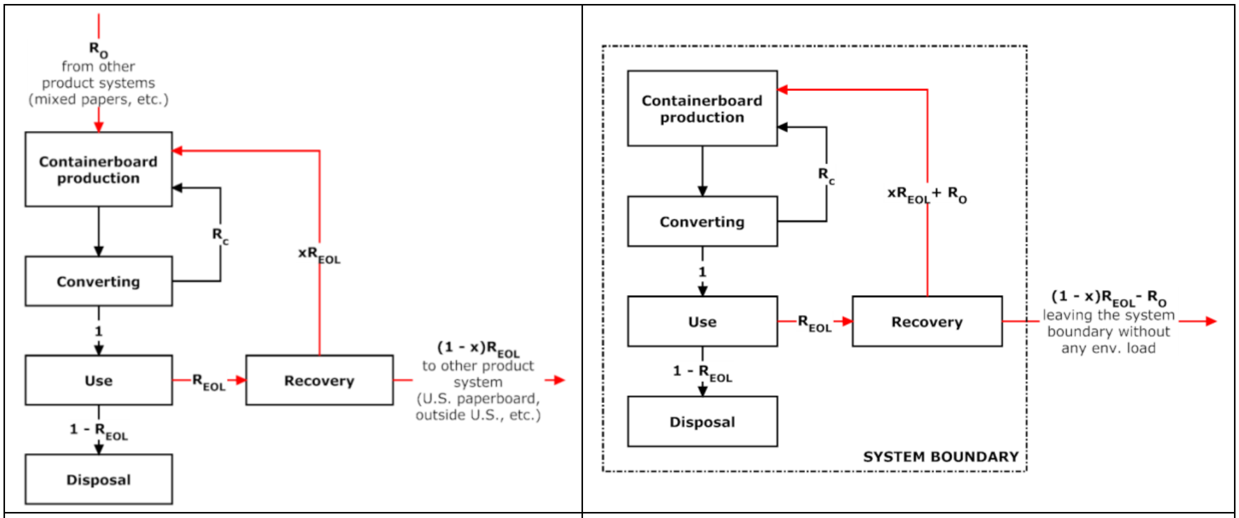
Several methods can be used for allocation related to open-loop recycling to determine how the environmental load from fresh fiber material production, recycling processes. and end-of-life should be distributed among the different products in the fiber life cycle (i.e., between fresh fiber and recycled products using the same fiber). More specifically, the ISO Standard provides the following examples: apply a closed-loop procedure to an open-loop system (if applicable), use a physical property as the basis for allocation, employ the economic values of the fresh fiber and recycled material, or apply the number of subsequent uses of the recovered material. Methodological choices in LCA, including the choice of allocation procedures, need to be consistent with the goal of the study. This study included two main objectives: (1) to document the environmental attributes of the industry-average corrugated product over time, and (2) to present the environmental performance of a corrugated product made of 100%-recycled fiber relative to that of the industry-average recycled content. These two different objectives required the selection of an allocation method to be made separately.

Evaluation of the Industry-Average Corrugated Product

The approach that was used in this study for the industry-average product is illustrated in Figure 12. It was first assumed that the entire need for recovered fiber in containerboard production was fulfilled from converting wastes and old corrugated containers recovered at their end-of-life

(Closed-Loop Approximation). In other words, no other recovered fiber sources from outside the system boundary (e.g., mixed papers) were considered for allocation purposes. In doing so, no environmental load from other product systems was considered to come with the use of recovered fiber. Also, there was a net export of recovered fiber to other systems because more old corrugated containers were recovered than the containerboard production process actually needed. It was assumed that this net export of recovered fiber left the system boundary without an environmental load associated with it. This is a conservative approach that avoids distorting the system impacts. This is often referred to as the Cut-Off or Recycled-Content Method.

This method is not specifically mentioned in the ISO 14044 Standard, or its accompanying ISO 14049 Technical Report. However, the ISO Standard is not stringent regarding which allocation method should be applied. It was selected because it is the method that best describes the direct environmental load from U.S. corrugated production without any distortions from potential interactions with other product systems. Also, it does not require complex assumptions, as would have been the case for other methods.



(a) **(b)**

Figure 12. Schematic Illustration of Open-Loop Recycling Allocation Method Used in this Study a) Actual Product System, b) Product System Modeled for Open-Loop Recycling
(In this figure, the flows of recovered fiber are shown in red. R_o is the quantity of recovered fiber imported from other product system, R_c is the converting wastes, R_{EOL} is the quantity of old corrugated containers recovered at their end-of-life, and x is the fraction of this quantity that is recovered within U.S. containerboard production.)

<u>Expressing the Environmental Performance of the 100%-Recycled Content Corrugated Product Relative to that of the Industry-Average Recycled Content Corrugated Product</u>

When performing the LCA on the industry-average corrugated product, it was not necessary to distribute the environmental loads from fresh fiber production, recycling processes, and end-of-life between products with different recycled fiber contents, at least within the corrugated product system. When attempting to express the environmental performance of the 100%-recycled corrugated product relative to that of the industry-average product, however, it is necessary to make a decision on how these environmental loads should be distributed. There are several different methods that can be used, none of which have gained consensus as a favored method. Furthermore, it has been demonstrated that the selection of an allocation method is critical to a comparison of products with different recycled fiber contents (e.g., Galeano et al. 2011, National Council for Air and Stream Improvement 2012).

The ISO 14044 Standard (ISO 2012b, p. 14) specifies that *"whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach."* For this reason, in this study, two methods that each express a different perspective have been applied to express the environmental performance of the 100%-recycled product relative to that of and the industry-average product: the Closed-Loop Approximation w/ Cut-Off Method, also used for the industry-average LCA and described above, and the ISO 14049 Number of Uses Method (ISO 2012b). The Number of Uses Method:

- Was specifically developed with paper products in mind and is the only one that directly addresses the complex relations between fresh fiber and recycled fiber;
- Has been recommended by an international working group addressing LCI issues as the recommended practice for recycling, especially in cases where the objective is to compare products with various recycled fiber contents (American Forest & Paper Association 1996, National Council for Air and Stream Improvement 2010); and
- Is directly specified as an option in the ISO 14044 Standard.

The Cut-Off and Number of Uses Methods express different perspectives on how environmental loads should be distributed among fresh fiber and recycled products and, as a result, using the two methods is expected to give an adequate range of possible results. The two methods are summarized in Table 8.

Table 12. Comparison of the Cut-Off and Number of Uses Methods

	Cut-Off	**Number of Uses**
Fresh fiber production process	Allocated to the fresh fiber product	Allocated proportionally to all uses of the fiber
Recycling process	Allocated to the recycled product	Allocated to the recycled product
End-of-life	Allocated to the product system in which it occurs	Allocated to the product system in which it occurs
Perspective	Each product system should be assigned only the environmental load directly caused by that system, Promotes the use of recycled material as long as the environmental load of the recycling is lower than that of fresh fiber material production,	Fresh fiber material production is necessary to obtain resources that are valuable to multiple product systems, Promotes the use of recyclable products and end-of-life recovery for recycling,

More details regarding the application of each method are presented in Appendix F.

3.6 Data Quality Requirements

The main data quality requirements are presented in Table 13. These are based on the updated pedigree matrix approach by U.S. EPA (Edelen and Ingwerse 2016). The correlation of these quality indicators with ISO requirements is shown in the table. In addition, in alignment with the ISO Standard, consistency and reproducibility will be discussed, data sources will be reported, and uncertainty will be addressed. While for non-comparative assessment ISO does not specify which data quality indicators should be included for stand-alone LCAs, the study included an evaluation of all data quality indicators to facilitate future comparative assessment as this is required for that type of LCA.

Table 13. Data Quality Requirements

Data Quality Indicator	**Corresponding ISO requirement**	**Score**				
		1	**2**	**3**	**4**	**5**
Reliability	Precision Completeness	Verified data based on measurements	Verified data partly based on assumptions/calculation OR non-verified data based on measurement	Non-verified data partly based on qualified estimates	Qualified estimates; data derived from theoretical information	Non-qualified estimates
Temporal correlation	Time related coverage Representativeness	< 3 years difference to the reference year	< 6 years difference to the reference year	< 10 years difference to the reference year	< 15 years difference to the reference year	Age of data unknown OR > 15 years difference to the reference year
Geographical correlation	Geographical coverage Representativeness	Same resolution and area of study	Within one level of resolution and a related area of study	Within two levels of resolution and a related area of study	Outside of resolution but related to area of study	From a different or unknow area of study
Technological correlation	Technology coverage Representativeness	All technology categories are equivalent	Three of the technology categories are equivalent	Two of the technology categories are equivalent	One of the technology categories are equivalent	None of the technology categories are equivalent
Representativeness/ Data collection methods	Completeness Representativeness	Representative data from >80% of the relevant market[5], over an adequate period	Representative data from > 50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered OR > 50% of sites but for shorter periods	Representative data from only one site relevant for the market considered OR some sites but for shorter period	Representativeness unknown or data from a smaller number of sites AND from shorter period

(Table continued on next page.)

Table 13. (Cont'd)

Data Quality Indicator	**Corresponding ISO requirement**	**Score**				
		1	**2**	**3**	**4**	**5**
Technological correlation	Technology coverage Representativeness	Data from enterprises, processes and material under study (i.e., identical technology)	Representative data from 60-79% of the relevant market , over an adequate period OR representative data from >80% of the relevant market, over a shorter period of time	Representative data from 40-59% of the relevant market, over an adequate period OR representative data from 60-79% of the relevant market, over a shorter period of time	Representative data from <40% of the relevant market, over an adequate period of time OR representative data from 40-59% of the relevant market, over a shorter period of time	Unknown OR data from a small number of sites AND from shorter periods
Process review	N/A	Documented reviews by a minimum of two types of third party reviewers	Documented reviews by a minimum of two types of reviewers, with one being a third party	Documented review by a third-party reviewer	Documented review by an internal reviewer	No documented review
Process completeness	Completenss	>80% of determined flows have been evaluated and given a value	60-79% of determined flows have been evaluated and given a value	40-59% of determined flows have been evaluated and given a value	<40% of determined flows have been evaluated and given a value	Process completeness not scored

3.7 Comparison between Systems

In this study, two comparisons between systems were performed. The first one consisted of comparing the environmental performance of the industry-average corrugated product produced in 2006, 2010, 2014, and 2020. This comparison does not qualify as a comparative assertion under ISO 14044. Although the basis weight varies from year to year, the products made in year 2006, 2010, 2014, and 2020 were assumed to be functionally equivalent for comparison purposes. In practice, a lower basis weight (such as observed in 2014 and 2020) may have meant that less product is required to fulfill the same function if the functional unit would have been expressed in surface or volume of packaging. Hence, the approach taken for comparing corrugated product produced in different years was conservative, as the basis weight goes down over time. Note also that data collection procedures and other methodological considerations were not fully compatible for the 2006 study in comparison to the 2010, 2014. and 2020 studies.

The second comparison consisted of expressing the environmental performance of the 2020 100%-recycled product relative to that of the 2020 industry-average product. This comparison qualifies as a comparative assertion under the ISO 14044 Standard. In a comparative study, according to the ISO 14044 Standard, the equivalence of the systems being compared must be evaluated before interpreting the results. For undertaking that comparison, it was assumed that 1 kg of 100%-recycled corrugated product was functionally equivalent to 1 kg of industry-average product. Consequently, products were compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment.

4. LIFE CYCLE INVENTORY

4.1 Data Collection Procedures, Main Data Sources and Validation

In this section, the data collection procedures for foreground and background processes are explained. Foreground processes are those for which specific data were collected (i.e., containerboard production and converting), while background processes are those for which secondary data sources were used (e.g., chemical production, purchased energy production, etc.). More details on data collection for the 2006, 2010, and 2014 model can be found in their final reports (https://www.fibrebox.org/life-cycle-assessments).

4.1.1 Data Collection Procedure: Foreground Processes

Data collection was performed as follows for containerboard production:

- Data on water inputs, environmental loads, solid waste management, and energy (quantity and types of fuels) for the relevant pulp and paper mills were drawn from responses to the 2020 AF&PA Environmental, Health, and Safety Survey.
- Information on quantity of energy used, fiber input, furnish production, and chemical consumption (quantity and type) at the department level were collected in a supplemental survey.
- Data regarding the emissions of toxic substances (as defined by the U.S. Toxics Release Inventory) were modeled using U.S. LCI and NCASI information (NCASI 2001, NCASI 2015, NREL 2012).
- Data on nutrient content of treated wastewater effluents from pulp and paper mills were derived from available information in the U.S. EPA Permit Compliance System database (https://www.epa.gov/enviro/pcs-icis-overview); these data are insufficient to allow characterization of effluents from the specific mills in the database, but they do allow general characterization of effluents from U.S. pulp and paper mills.
- Data submitted by the industry in connection with the TSCA Inventory Update Rule (IUR, www.epa.gov/iur/) were used to estimate quantities of kraft pulping co-products produced (e.g., tall oil and turpentine); the IUR data were not sufficient to enable characterization of every mill in the database, but were sufficient to characterize kraft pulping processes in general.

The converting facilities for producing corrugated products in the U.S. were surveyed to collect energy and material input information, production, and environmental release information.

Data were recorded as production-weighted means.

It is important to note that no industry survey of the scope of U.S. containerboard production can achieve 100% coverage of operating facilities. Facility participation differences among survey years can obscure or magnify time series LCA results. It is the intention of this work to achieve the greatest participation of containerboard facilities and converter operations possible, leading to the most accurate picture of industry-average performance.

4.1.2 Data Collection Procedure: Background Processes

Background processes were modeled using publicly available life cycle inventory databases. The strategy employed to select which database to use is depicted in Figure 13. In summary, the U.S. LCI database (NREL 2012) was used as a priority because it is the main source of U.S.-specific life cycle inventory data. NCASI updated the data for electricity production with the most recent available data. The GaBi Professional database (PE Content, © PE International) was used as a secondary option based on the study commissioner's preference (PE INTERNATIONAL AG 1992-2013). Finally, the ecoinvent 2 database (Frischknecht et al. 2005) was used to fill any remaining data gaps. As the use of different databases can lead to inconsistencies, a verification of relative significance was made when either the GaBi Professional database for a non-U.S. dataset or the ecoinvent database was used.

A detailed list of unit processes used is presented in Appendix C.

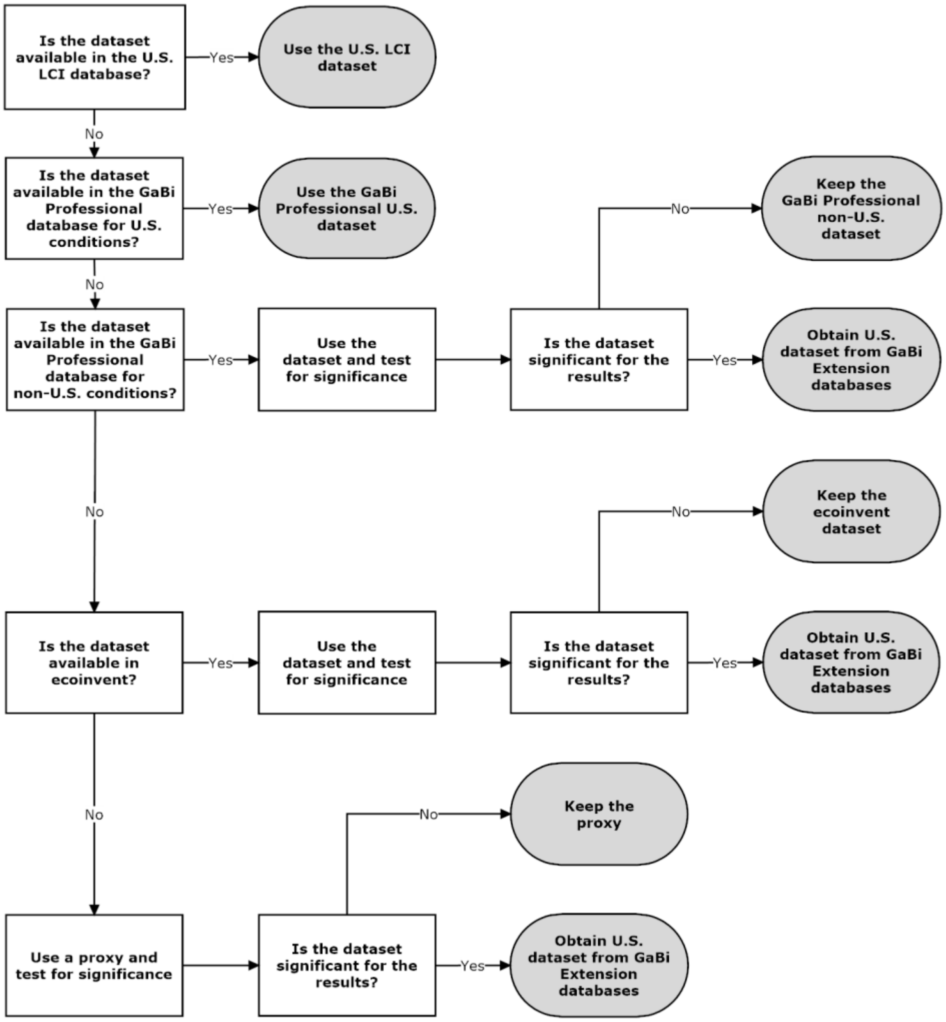


Figure 13. Data Collection Strategy for Background Processes

4.1.3 Summary of Data Sources

Primary data sources are summarized in Table 14.

Table 14. Primary Data Sources

Data required	Data source or assumption(s)
FOREGROUND SYSTEM – Containerboard production	
Material inputs	Supplemental survey
Air releases: Non-toxic	AF&PA Environmental, Health and Safety (EH&S)
Air releases: Toxic	Modeling based on U.S. LCI and NCASI information
Water releases: Non-toxic	EH&S, other sources
Water releases: Toxic	Modeling based on U.S. LCI and NCASI information
Energy data	EH&S
Mill solid waste	EH&S
Mill solid waste management and soil releases	EH&S and modeling based on U.S. LCI and NCASI information
Co-product quantity (e.g., turpentine)	TSCA IUR industry submissions supplemented with literature data as necessary
FOREGROUND SYSTEM – Converting	
All necessary information	Converting facilities questionnaire
BACKGROUND SYSTEM	
Forest operations	CORRIM (Johnson et al. 2004, Oneil et al. 2010) as available in the U.S. LCI database
Chip production	CORRIM (Bergman and Bowe 2010, Milota 2004, Milota et al. 2004, Puettmann et al. 2010) as available in the U.S. LCI database
Chemical and fuel production	Publicly available LCI databases
Electricity production	Weighted grid developed using containerboard/converting facilities' location U.S. LCI and GaBi databases
Corrugated product end-of-life	Ratios based on U.S. average NCASI information supplemented with publicly available databases
TRANSPORTATION	
Distances and modes	2017 U.S. Commodity Flow Survey (United States Department of Transportation and United States Department of Commerce 2020)
Transportation processes	U.S. LCI database

4.1.4 Energy Considerations

Energy requirement calculations were made using higher heating values (HHVs). HHVs account for the total heat content of a fuel when it is burned, some of which provides useful energy to the system in which the fuel is burned and some of which is used to evaporate the water in the combustion products. For life cycle assessment purposes, HHV is a more complete method of energy accounting compared to using the lower heating value (LHV), as LHV does not account for the energy content of the fuel that was used to evaporate the water formed in combustion. For this reason, HHVs were used in this study. The following table summarizes assumptions and data regarding heating values.

Table 15. Heating Values of Fuels for the 2020 Dataset

Material	**Unit**	**Higher Heating Value* (MJ HHV/unit)**
Purchased hogged fuel, logging residues	kg	20.9
Purchased hogged fuel, manufacturing residues	kg	18.6
Self-generated hogged fuel, logging residues	kg	20.9
Self-generated hogged fuel, manufacturing residues	kg	18.6
Wastewater treatment plant residuals	kg	15.1
Spent liquor solids	kg	15.6
Non-recyclable paper	kg	17.4
Other biomass	kg	18.6
Bituminous coal	kg	37.2
Distillate fuel oil (#2)	L	39.0
Gasoline	L	34.8
Liquid propane gas	L	25.5
Natural gas	m^3	38.4
Residual fuel oil (#5, 6)	L	41.8
Rubber tire chips	kg	30.2

**Higher heating values are from AF&PA EHS survey and based on dry weights.*

4.1.5 Carbon Contents

Table 16 summarizes data and assumptions regarding the carbon contents of the various materials modeled in this study. Some carbon contents were calculated. The details on these calculations can be found in Appendix B.

Table 16. Carbon Contents of Various Materials

Material	Carbon content	Comment/Source
Wood inputs	50.0%	IPCC (IPCC 2006b, Table 2.4)
Containerboard	49.6%	Calculated by assuming 50% of the fiber content (IPCC 2006b, Table 2.4) and the carbon in added starch. Fiber content was calculated by subtracting the paper additive quantity from the weight of the product. Other sources of carbon were neglected.
Corrugated product and OCC (2020)	49.7%	Carbon contents of corrugated products were calculated using carbon balances.
Black liquor	35.0%	The carbon content of black liquor is variable. A value of 35.0% was used as a first approximation (NCASI 2005). Black liquor carbon content was adjusted to close the carbon balances (see details in Appendix B.2)
Fresh fiber market pulps	50.0%	50% of fiber (IPCC 2006b, Table 2.4).
Recycled market pulps	43.1%	Printing and Writing LCA study (NCASI 2010).
Starch	44.4%	Carbon content was set based on the basic chemical formula of the starch molecule that is $(C_6H_{10}O_5)_n$.
Wastewater treatment plant/deinking residuals	49.0%	Literature review (NCASI 2013a)

4.1.6 Validation of Data

The ISO 14044 Standard requires that a check on data validity be conducted during the process of data collection. The objective is to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled. Validation may involve establishing, for example, mass balances, energy balances, and/or comparative analyses of release factors.

4.1.6.1 Quality Assurance

Containerboard Mill Survey

Surveys requesting detailed production and energy and raw material input information were received from 51 containerboard mills. Information provided via the surveys was quality-assured (QA) using a combination of cross-checking with data previously submitted to the AF&PA Environmental, Health and Safety (EHS) survey (which had previously been subjected to a quality-assurance protocol) and by evaluating internal consistency of various data elements based on engineering principles, as summarized below. Issues identified during the QA process were investigated through follow-up correspondence with mill and corporate staff. Where issues could not be sufficiently addressed, the related survey information was omitted from the study. This process resulted in the inclusion of data for all the 42 containerboard mills.

1. The following survey entries were compared to those submitted to the EHS survey:
    a. Total production.
    b. Total energy consumption at the facility.

    c. Total water intake entries were compared to total effluent discharge submitted to the EHS survey.
2. Entered quantities of fiber furnish produced on-site were correlated with entered quantities of fiber (wood, recovered paper, etc.) via yield calculations. Additionally, all entered fiber input elements were correlated with furnish elements used in production.
3. Entered quantities of steam consumption were correlated with entered quantities of on-site steam generation, taking into account steam purchases as independently submitted to the EHS survey.
4. Entered energy consumption for various mill processes was correlated with product types (and with on-site electricity production) to ensure consistency.
5. Entered values for water content of various input materials were evaluated.
6. In addition, a "hidden" calculation page embedded in the survey was used to identify any elements where the respondent may have inadvertently modified formulas integral to the survey.

Converting Facility Survey

Surveys requesting detailed production, energy and raw material input, and environmental releases (including material outputs recycled by other facilities) were received from 402 converting facilities. The information provided via the surveys was quality-assured by evaluating internal consistency of various survey data elements based on engineering principles and by comparing with average or median values reported by similar facilities, as summarized below. Issues identified during the QA process were investigated through follow-up correspondence with facility and corporate staff. The process resulted in the inclusion of data for 264 corrugator plants, 106 sheet plants, and 32 sheet-feeder plants (total of 166 converting facilities).

1. A mass balance was performed considering all input materials and outputs of corrugated sheets, finished corrugated products, recycled materials, and solid waste. Agreement of inputs and outputs within 10% was required for a facility's survey information to be included in the analysis.
2. Energy consumption data entry elements underwent a two-step QA process. Initial evaluation consisted of comparing entries to those of other similar facilities to identify gross errors (e.g., departures of at least one order of magnitude from those of similar facilities) typically associated with erroneous measurement unit entry. Secondary evaluation consisted of identifying potential outliers using statistical outlier tests of total energy intensity (e.g., Dixon's test). As outlined above, facilities that submitted suspect information were contacted for clarification/confirmation of the information.
3. Entered values for water content of various input materials were evaluated.
4. Entered values for various input materials were evaluated for reasonableness (for example, a sheet feeder plant is expected to consume liner and medium in producing corrugated sheets, whereas a sheet plant is expected to consume corrugated sheets in producing finished corrugated products).

5. Entered values for water intake to the facility were compared with entered values for water releases from the facility.

Parameters Used in Life Cycle Assessment

The quality-assured data received from containerboard mills and from converting operations were used to develop production-weighted mean (PWM) environmental burdens and other parameters required for input to life cycle assessment models for various product grades. The calculations associated with these parameters were internally reviewed by NCASI staff not involved with the development of the calculation methods. In addition, because two years of data were available derived from similar methodologies, it was possible to perform additional QA. While comparing LCA results for 2014 and 2010, it was possible, to some extent, to check and correct some calculations for the 2014 and 2010 LCA model. Incremental improvements and minor error corrections have been made to the data aggregation approach and quality assurance of the LCI dataset based upon comparison of the 2020 LCA results with the 2014 and 2010 results.

4.1.6.2 Mass Balances

Water, fiber, and carbon balances were performed for the containerboard production and converting unit processes. Where adequate, the results of the mass balances were used to correct the collected data. More details can be found in Appendix B.

4.1.6.3 Treatment of Missing Data and Cut-Off Criteria

In theory, an LCA study should track all processes in the life cycle of a product, but this is not possible in practice. For this reason, some flows are commonly ignored or “cut off.” The CML guide (Guinee et al. 2002) distinguishes two distinct aspects of cut-off criteria: (1) unit processes for which there are no data, and (2) interventions from relevant unit processes for which there are no data. The following cut-off procedure was applied in this study:

1. Cut-offs were, as much as possible, avoided by collecting process-specific data.
2. Where no process-specific data were found for a given process, estimates were based on a similar process.
3. When estimation was not possible, the flow was cut off and the potential significance of this cut-off assessed (qualitatively or quantitatively).

In addition, specific data were collected for containerboard production processes and manufacturing of final products (converting). The data collection was performed in a way that ensured that any flow contributing to more than 1% of the mass inputs of those processes was included, except for chemicals. Knowledge gained during the previous LCA effort, in terms of the point after which additional data do not add measurable benefit to the robustness of the final LCA results, justified the assessment to include only those chemicals contributing more than 10% of the total dry mass of chemicals used in each containerboard component. In this manner, no chemicals with significant individual contribution to any environmental indicator (i.e., > 5%) would be ignored. Using that cut-off criteria, the following list of chemicals, for which data were collected, was developed:

- Aluminum sulfate;
- Caustic (sodium hydroxide);
- Starch;
- Sulfuric acid;
- Strength agents (wet and dry);
- Lime;
- Soda powder; and
- Pitch dispersants.

In addition, the mills were asked to report the total mass of "other fillers", to calculate the average carbon content of containerboard. No significant energy input was omitted. All known air-related substances associated with combustion, which are deemed significant through U.S. EPA’s TRI (SARA 313) regulation and other national and international combustion-related air contaminant programs, were included for containerboard production and, to the extent they were documented in the selected databases, for other unit processes.

The ISO 14044 Standard also requires that the system boundaries be refined to include processes initially excluded but of potential significance to the results. No unit processes were excluded.

4.2 Detailed Description of the Product System and Related Unit Processes

4.2.1 Raw Material/Energy Acquisition: Wood Fiber

The main raw material used for the production of containerboard is wood fiber (fresh fiber or recycled). Table 17 presents a summary of woody material used to produce 1 kg of corrugated product (CP) or 1.09 kg of containerboard in 2020. Containerboard made from 100%-recycled fiber does not use logs and chips for pulp production. However, some of the containerboard from 100%-recycled fiber is produced at mills that also produce containerboard from fresh fiber. Some of these mills produce more energy using spent liquor and self-generated hogged fuel than they need in their fresh fiber operations. In these cases, it was assumed that extra energy from these fuels was "sold" to the recycled product and hence, the quantity of chips and logs required to produce that sold energy was allocated to the recycled product.

More details on the fiber types used for containerboard production can be found in Appendix D.

Table 17. Woody Material Inputs per Functional Unit

Fiber Type	Quantity (kg/kg Corrugated Product or 1.09 kg Containerboard)						
	Industry-Average				100%-Recycled		
	2020	2014	2010	2006	2020	2014	2010
Wood Inputs							
Hardwood logs[a]	0.11	0.14	0.14	0.13	≈ 0.00[c]	≈ 0.00[c]	0.00
Softwood logs[b]	0.59	0.58	0.69	0.43	0.01[c]	≈ 0.00[c]	0.07[c]
Purchased hardwood chips[b]	0.05	0.10	0.13	0.12	0.00	0.00	0.01[c]
Purchased softwood chips[b]	0.28	0.32	0.35	0.48	0.00	0.00	0.00
Total wood inputs	***1.03***	***1.14***	***1.31***	***1.17***	***0.01***	***0.00***	***0.08***
Recovered Paper							
Recovered paper	0.62	0.57	0.51	0.46	1.27	1.23	1.25
Purchased Pulps							
Fresh fiber	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00
Recycled	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00
Total purchased pulps	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00	≈ 0.00

NOTE: Compared to the previous report, 2010 data were corrected to account for an error in the board mix calculation.

[a] *Includes the fraction of the log used for energy (e.g., bark).*

[b] *As opposed to self-generated chips for which the wood quantity is accounted for in logs.*

[c] *Transferred from other products for energy purposes.*

4.2.1.1 Forest Operations

The forest operations unit processes are described in reports from the Consortium for Research on Renewable Industrial Material (CORRIM) (Johnson et al. 2004, Oneil et al. 2010). Forest operations include the establishment of hardwood and softwood forest stands, the treatment of those stands through to maturity, and the harvesting of logs from the stands. Data related to stand management incorporate aspects related to the preparation of the site for planting, the planting of seedlings on the harvested site, and intermediate stand treatments to enhance growth and productivity (thinning or fertilization or both). As modeled in CORRIM's reports, harvesting consists of:

- felling (severing the standing tree from the stump);
- processing (de-limbing and/or topping, and cutting of the tree into merchantable and transportable log lengths);
- secondary transportation (moving trees or logs from the point of felling to a loading point near a haul road); and
- loading (moving logs from loading point to haul vehicles).

The production of the inputs (seedlings, fuel, lubricants, etc.) is also included in this unit process. The inventory data developed by CORRIM are the main source of information for modeling forest operations.

4.2.1.2 Purchased Chip Production

This unit process includes debarking/chipping of roundwood in off-site chipmills and production of chips as a co-product at sawmills[8]. It does not include chipping operations at pulp and paper mills. CORRIM is the main source of inventory data for modeling the forest and chip production unit processes. However, CORRIM does not provide data for chips produced at chipmills. Hence, it has been assumed that all chips produced off-site are co-products of sawmills. Sawmills can be broken into three main operations: sawing, drying, and planing. Chips are produced as a co-product of the first operation (sawing), which consists of transforming the logs into green lumber.

4.2.1.3 Supply of Recovered Fiber

In 2006, 2010, 2014, and 2020 there were some differences in utilization rates of recovered fiber:

- 2006 fiber data were obtained from Fisher International but did not match AF&PA statistics on recovered fiber utilization rate[9]. Hence, Fisher fiber data were adjusted to match AF&PA recovered fiber utilization rate, i.e., **0.42 kg/kg of containerboard** or 0.46 kg/kg corrugated product.

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[8] Environmental load of the sawmilling process is mass allocated between its co-products (lumber, chips, wood wastes).

[9] Utilization rate: quantity of recovered fiber used per unit of production.

- Based on the survey data collected directly from the mills, the utilization rate in 2010 was **0.46 kg/kg** containerboard produced and used in the U.S. (or 0.51 kg/kg of corrugated product). This represents a utilization rate of approximately **0.47 kg/kg** total containerboard produced in the U.S. This compares to a value of **0.47 kg/kg** containerboard reported by AF&PA.
- Based on the survey data collected directly from the mills, the utilization rate in 2014 was **0.52 kg/kg** containerboard produced and used in the U.S. (or 0.58 kg/kg of corrugated product). This resulted in a utilization rate of **0.48 kg/kg** total containerboard produced in the U.S. This compares to a value of **0.47 kg/kg** containerboard reported by AF&PA (2015).
- Based on the survey data collected directly from the mills, the utilization rate in 2020 was **0.56 kg/kg** containerboard produced and used in the U.S. (or 0.62 kg/kg of corrugated product). This resulted in a utilization rate of **0.52 kg/kg** total containerboard produced in the U.S. This compares to a value of **0.52 kg/kg** containerboard reported by AF&PA (2015).

Table 18 shows that recovered fiber used in 2020 containerboard production comes from three main sources: converting wastes, post-consumer old corrugated containers, and recovery from other product systems.

Table 18. Types of Recovered Paper Used in Containerboard Production (2020)

Grade of Recovered Paper	Description	Share of Total Recovered Paper Used
Converting wastes (pre-consumer OCC)	Consists mainly of double-lined kraft (DLK), i.e., clean, sorted, unprinted, corrugated cardboard cartons, boxes, sheets, or trimmings. Must be kraft or jute liner content.	20.5%
Post-consumer old corrugated containers (OCC)	Consists of corrugated containers having liners of either test liner, jute, or kraft	64.0%
Mixed papers	Broad category that often includes items such as discarded mail, telephone books, paperboard, magazines, and catalogs	12.2%
Pulp substitutes	High-grade paper that often consists of shavings and clippings from converting operations at paper mills and print shops	≈0.0%
High Grade De-inking	High grade paper such as letterhead, copier paper, envelopes, and printer and convertor scrap that has gone through the printing process.	3.3%

The recovered fiber supply consists of the sorting of used paper (usually from municipal solid waste) and transportation to pulp and paper mills. Sorting operations were neglected for two reasons: (1) there are no data available concerning how much paper comes from municipal sorting operations versus industrial operations, and (2) sorting operations are not expected to be significant to the study results.

4.2.2 Raw Material/Energy Acquisition: Chemicals

Chemicals used in the various life cycle stages are presented in the respective sections of these life cycle stages. Chemical production processes were modeled using secondary data sources (see Section 4.1.2 and Appendix C for more details).

4.2.3 Raw Material/Energy Acquisition: Energy

4.2.3.1 Purchased Electricity

Electricity production was modeled differently for the foreground processes (containerboard production and converting) than for the background processes (all others). The modeling differences are described below.

Foreground Processes

For the containerboard mills, purchased electricity was assigned upstream loads for the electrical grid serving the specific facilities on which the LCA is based (based on eGrid regions). Containerboard facility location was used to determine the applicable region-specific emission factor. Facility electricity use by product (prorated by production mass) was then used to develop the overall electricity mix by product grade, which was different for the industry-average corrugated products and the product made from 100%-recycled fiber, as shown in Table 19.

Table 19. Electricity Mix for Industry-Average and 100%-Recycled Containerboard

eGrid Region	**Industry-Average**	**100%-Recycled**
	% of the total purchased electricity obtained from each e-grid region	
East	75.3%	98.3%*
West	19.7%	1.7%*
Texas	5.0%	0%*

**According to data from Fisher International and given the board mix considered in this study, approximately 22% of the 100%-recycled containerboard is produced in the West or in Texas. This indicates that the production of the products from these regions was poorly represented in the collected data. At the industry-average level, the products from the East region are also slightly under-represented, but to a lesser extent. Electricity grid mixes can have significant effect on the results of an LCA. For this reason, sensitivity analyses were included to test the potential effects of this on the results.*

The load for electricity and steam sold by those facilities was not included in the study (see Section 3.5 for allocation procedures).

For converting mills, a 2020 U.S. average power mix was used because the representativeness was lower and because facilities are spread out across the nation.

Background Processes

For all other processes, an average 2020 U.S. grid was used.

Modeling of Electricity Production

The U.S. average, East, West, and Texas consumption grid mixes were modeled using processes from the U.S. LCI database. They were calculated by considering the quantity of power produced in the U.S. by type of fuel, the quantity of power exported, and the quantity imported from Canada and Mexico. The production mix for the United States was calculated using 2020 data from the U.S. Department of Energy, Energy Information Administration (EIA 2021). Since electricity imports from Mexico represent less than 1% of the total energy consumed in the U.S., these data are not expected to have a significant effect on the results. 2014 Canadian data were taken from Statistics Canada 2022). Table 20 presents the fuel mixes for U.S. average, East, West, and Texas electricity consumption, as well as the datasets that were used to model them.

Table 20. U.S. Average Electricity Grid Fuel Consumption Mix

Fuel type	%				Dataset used
	U.S.	East	West	Texas	
Coal (including CHP)	19.1	20.2	16.3	16.6	Electricity, bituminous coal, at power plant /US
Petroleum	0.3	0.3	0.2	0.0	Electricity, residual fuel oil, at power plant/US
Natural gas (including CHP)	40.2	39.8	34.1	51.5	Electricity, natural gas, at power plant /US
Nuclear	19.7	24.7	7.8	8.7	Electricity, nuclear, at power plant/US
Hydroelectric	7.7	5.3	22.2	0.9	Electricity, hydropower, at power plant/SE (89%), and Electricity, hydropower, at pumped storage power plant/US (11%), from ecoinvent
Wind	8.4	6.4	8.9	19.2	Electricity, at wind power plant/RER, from ecoinvent
Wood and wood-derived fuels (CHP)	1.4	1.6	1.3	0.3	Electricity, biomass, at power plant/US
Others	3.2	1.7	9.3	2.7	As appropriate

4.2.3.2 Purchased Steam

The EIA methodology[10] was used to update the purchased steam GHG emission factor with 2018 US Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS) information: “Weighted average based on Energy Information Administration’s (EIA) 1998 Manufacturers Energy Consumption Survey data on the quantities of natural gas, coal, and residual and distillate fuel oils consumed as boiler fuel, carbon coefficients provided in EIA's. Assumptions to the Annual Energy Outlook 2003, and EIA/OIAF efficiency assumptions of 80, 81, and 82 percent for natural gas, coal and petroleum boilers, respectively. The GHG emission factor value also includes 10 percent loss during transmission.”

4.2.4 Pulp and Papermaking Operations

Pulp and papermaking operations consist of different unit processes that are depicted in Figure 14. The figure shows the 2020 industry-average product. Each of the unit processes and "sub-unit processes" are described in detail in the following sections.

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[10] https://www.eia.gov/survey/form/eia_1605/form.pdf

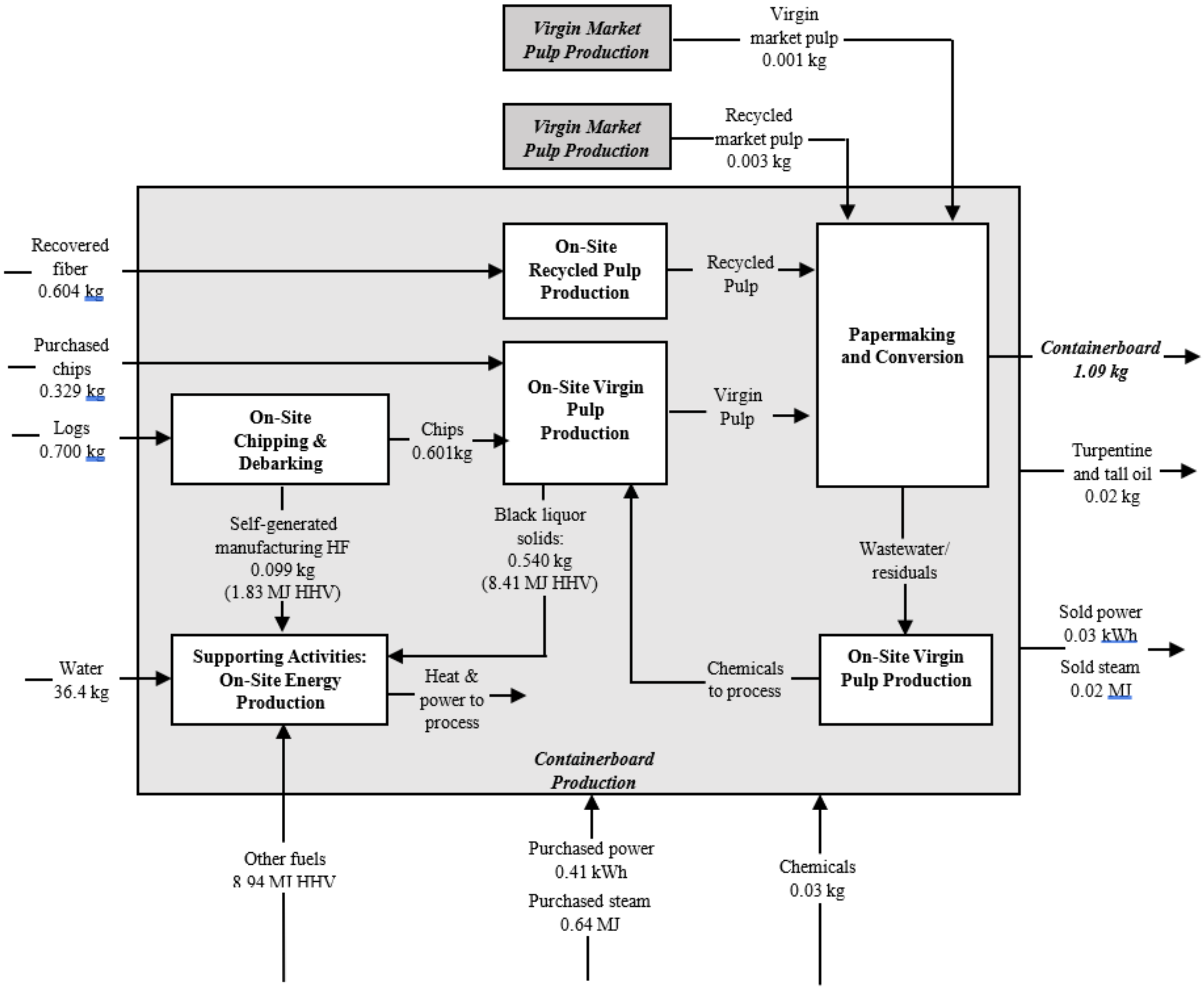

Figure 14. Schematic of Pulp and Papermaking Operations Life Cycle Stage, 2020 Industry-Average (Modeled unit processes are depicted in gray)

4.2.4.1 Market Pulp Production

Some of the fiber requirements are fulfilled using market pulps, both fresh fiber and recycled. Market pulps are pulps produced off-site and transported to containerboard mills.

4.2.4.2 Containerboard Production

The containerboard production unit process consists of several sub-unit processes: debarking and chipping, on-site fresh fiber pulp production, on-site recycled pulp production, papermaking and conversion, and supporting activities. While these subcomponents of the containerboard production unit process are described in the next paragraphs, Table 21 presents a summary of the inputs and outputs to the unit processes. The details of all inputs and outputs can be found in Appendix D for 2014.

Table 21. Inputs/Outputs to Containerboard Production Unit Process per Functional Unit

Input/Output	**Quantity**						**Unit**[11]	**Comment**
	Industry-Average			**100%-recycled**				
	2020	**2014**	**2010**	**2020**	**2014**	**2010**		
INPUTS								
Resources								
Water intake	36.4	30.9	37.5	6.91	8.49	10.5	kg	Includes process and cooling water.
Fiber Raw Material								
Total wood inputs	1.03	1.14	1.31	0.01	0.002	0.078	kg	As depicted in Figure 14, total wood inputs include logs and chips both from hardwood and softwood. A fraction of these inputs is used for energy through self-generated hogged fuel (manufacturing) and black liquor solids.
Self-generated hogged fuel manufacturing	*0.099 (1.83)*	*0.12 (2.30)*	*0.15 (2.75)*	*0.008 (0.15)*	*0.004 (0.07)*	*0.008*	*kg (MJ HHV)*	
Black liquor solids	*0.54 (8.41)*	*0.58 (8.89)*	*0.65 (9.71)*	*0.00 (0.04)*	*0.00 (0.00)*	*0.09 (1.37)*	*kg (MJ HHV)*	
Recovered fiber	0.62	0.57	0.51	1.27	1.23	1.25	kg	Includes OCC, mixed papers, pulp substitute and high-grade deinking (see Section 4.2.1.3 for more details).
Purchased pulp, fresh	0.001	0.001	0.001	0	0	0	kg	Includes bleached and unbleached kraft market pulp.
Purchased pulp recycled	0.003	0.004	0.002	0.002	0.001	0	kg	Recycled non-deinked pulp.
Chemicals								
Caustic	3.8E-3	7.6E-3	9.0E-3	8.7E-4	4.1E-4	4.4E-5	kg	
Sulfuric acid	6.7E-3	1.2E-2	1.1E-2	1.2E-5	7.0E-4	3.3E-3	kg	
Aluminum sulfate	1.3E-3	2.7E-3	3.3E-3	4.8E-4	9.2E-4	2.7E-3	kg	
Starch	6.7E-3	5.4E-3	3.4E-3	1.2E-5	6.1E-3	7.4E-3	kg	
Lime	1.7E-3	9.0E-3	4.4E-3	9.9E-6	0	0	kg	

(Table continued next page. See note at end of table.)

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[11] kg are dry kg, unless specified.

Table 21. (Cont'd)

Input/Output	**Quantity**						**Unit**[12]	**Comment**
	Industry-Average			**100%-recycled**				
	2020	**2014**	**2010**	**2020**	**2014**	**2010**		
Chemicals (Cont'd)								
Soda	8.4E-4	3.6E-3	1.2E-3	0	0	0	kg	
Pitch dispersant	7.4E-5	6.0E-5	2.00E-4	1.1E-4	0	4.7E-4	kg	
Strength agents	2.0E-3	7.0E-4	5.02E-4	6.7E-3	1.6E-3	1.7E-3	kg	
Other fillers	4.0E-3	5.5E-3	1.9E-3	1.7E-3	1.8E-3	1.9E-4	kg	Includes a variety of papermaking fillers (organic and inorganic)
Energy								
Renewable fuels	1.65	2.86	2.28	0.43	0.60	1.02	MJ HHV	Includes self-generated logging residues, purchased hogged fuel, as well as other renewable fuels. Self-generated hogged fuel (manufacturing) and black liquor solids are not included here but rather in total wood inputs above.
Fossil fuels	7.24	5.69	5.96	6.48	4.46	5.37	MJ HHV	Includes coal, natural gas, and a variety of other fossil fuels.
Purchased power	1.46	1.66	1.45	1.58	2.12	2.03	MJ	
Purchased steam	0.64	0.77	1.16	1.72	2.45	4.10	MJ	
OUTPUTS								
Products and co-products								
Containerboard	***1.09***	***1.10***	***1.11***	***1.09***	***1.10***	***1.11***	***kg***	Quantity of containerboard per functional unit
Turpentine and tall oil	0.023	0.017	0.018	0	0	0	kg	
Sold power	0.03	0.07	0.02	0.03	0	0.03	MJ	
Sold steam	0.02	0	0.02	0.02	0	0	MJ	

(Table continued next page. See note at end of table.)

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[12] kg are dry kg, unless specified.

Table 21. (Cont'd)

Input/Output	**Quantity**						**Unit**[13]	**Comment**
	Industry-Average			**100%-recycled**				
	2020	**2014**	**2010**	**2020**	**2014**	**2010**		
Emissions to air (process and combustion)								
Nitrogen oxides (NO_x)	1.28E-2	1.56E-3	1.83E-3	6.29E-4	7.31E-4	5.08E-4	kg	
Sulfur oxides (SO_x)	5.86E-4	1.15E-3	1.78E-3	1.81E-4	2.54E-4	4.07E-4	kg	
Total reduced sulfur (TRS), as H_2S	2.05E-4	7.71E-5	7.0E-5	7.07E-8	0	0	kg	
Particulates	4.86E-4	6.11E-4	7.20E-4	3.58E-5	5.03E-5	1.44E-4	kg	
Carbon monoxide (CO)	2.53E-4	2.57E-4	3.12E-4	2.19E-4	1.73E-4	2.10E-4	kg	
Carbon dioxide (CO_2), biogenic	1.00	1.23	1.38	0.071	0.104	0.075	kg	
Carbon dioxide (CO_2), fossil	0.370	0.331	0.386	0.320	0.235	0.311	kg	
Methane (CH_4), biogenic	2.90E-3	1.22E-3	1.65E-3	3.34E-3	2.24E-3	5.49E-4	kg	
Methane (CH_4), fossil	1.10E-5	1.3E-5	1.64E-5	5.91E-6	5.06E-6	7.22E-6	kg	
Nitrous oxide (N_2O)	3.07E-5	5.01E-5	6.28E-4	2.42E-6	6.64E-6	1.46E-5	kg	
Evaporated water	4.29	3.67	4.44	1.08	1.35	1.69	kg	Estimated.
Toxics	The releases of toxic substances (as defined by the U.S. Toxics Release Inventory) to air were estimated using NCASI data (NCASI 2001).							

(Table continued next page. See note at end of table.)

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[13] kg are dry kg, unless specified.

Table 21. (Cont'd)

Input/Output	Quantity						Unit[14]	Comment
	Industry-Average			100%-recycled				
	2020	2014	2010	2020	2014	2010		
Emissions to water								
Process effluent	30.5	26.8	27.5	4.97	6.82	8.29	kg	Cooling water is estimated. In some cases, cooling water discharges may have been included within effluent.
Cooling water discharges	2.57	1.82	6.84	0.88	0.36	0.58	kg	
Adsorbable Organic Halides (AOX)	1.77E-6	4.21E-6	5.12E-6	0	0	0	kg	
Biochemical oxygen demand (BOD5)	1.16E-3	9.73E-4	1.12E-3	1.03E-3	4.63E-4	5.57E-4	kg	
Total suspended solids (TSS)	1.18E-3	1.34E-3	1.57E-3	1.15E-4	1.46E-4	1.35E-4	kg	
Total nitrogen	2.44E-4	2.04E-4	2.21E-4	4.31E-5	5.09E-5	4.86E-5	kg	
Total phosphorus	3.69E-5	3.45E-5	3.44E-5	4.45E-6	5.12E-6	4.94E-6	kg	
Toxics	The releases of toxic substances (as defined by the U.S. Toxics Release Inventory) to water were estimated using NCASI data (NCASI 2001).							
Emissions to soil								
Toxics	The releases of toxic substances to soil (as defined by the U.S. Toxics Release Inventory) were estimated using NCASI data (NCASI 2001).							

(Table continued next page. See note at end of table.)

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[14] kg are dry kg, unless specified.

Table 21. (Cont'd)

Input/Output	**Quantity**						**Unit**[15]	**Comment**
	Industry-Average			**100%-recycled**				
	2020	**2014**	**2010**	**2020**	**2014**	**2010**		
Residuals								
Note: Landfill and burning were assumed to occur on site. Land application and other beneficial were assumed to occur offsite.								
Wastewater treatment plant residuals	0.017	0.036	0.052	0.006	0.064	0.105	kg	Burned: 10.1%, land applied: 46.1%, landfilled: 38.1%, other: 5.6%. 2020.
Wood ashes	0.014	0.023	0.046	0.002	0.003	0.007	kg	Land applied: 22.3%, landfilled: 55.8%, other: 21.9%
Coal ashes	0.000	0.006	0.010	0.000	0.002	0.003	kg	
Other solid wastes	0.081	0.049	0.0413	0.020	0.058	0.039	kg	Burned: 2.0%, land applied: 12.5%, landfilled: 60.9%, other: 24.7%. 2020.

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[15] kg are dry kg, unless specified.

Debarking and Chipping

Wood delivered to the containerboard mill as logs goes through a de-barking and chipping process to produce wood chips, in addition to chips sourced from sawmills and chip mills. These wood chips, processed to a uniform size, form the raw material for production of fresh fiber wood pulp. This pulp is used, often with additional pulp from recovered fiber, for making containerboard. Containerboard can also be produced from recovered fiber alone, as discussed below.

On-Site Fresh Fiber Pulp Production

Cooked in a high-pressure, high-temperature (130-180 °C) digester in a mixture of inorganic chemicals (e.g., sodium hydroxide, sodium sulfide, sodium sulfite, sodium carbonate, etc.) tailored for the desired pulp properties, the wood chips are broken down into wood pulp and spent pulping liquor, with a pulp yield depending on the chemicals used, desired containerboard properties, and cooking parameters.

The spent pulping liquor is washed from the pulp, then concentrated and burned to recover the cooking chemicals and provide heat required for containerboard production. The pulp is cleaned by a series of separation, screening, and washing steps before being moved to the containerboard-making process (i.e., the paper machine). At the paper machine, pH is adjusted and additives such as sizing agents are introduced to the pulp slurry to give the final sheet its desired properties.

On-Site Recycled Pulp Production

The recovered paper that is delivered to the containerboard mill is controlled for quality and contaminants before being re-pulped. Re-pulping involves breaking and dispersing the recovered paper bales and loose-fed material in warm process water using mechanical energy. Large pieces of plastic, wires, and other materials may be removed within the re-pulping operation using a ragger and other de-trashing equipment. The resulting "stock," a suspension of fiber in water, is then screened through progressively smaller holes and slots and sometimes cleaned centrifugally to remove sand, grit, and lightweight contaminants. Some recycled containerboard mills fractionate and possibly wash the stock to generate streams enriched in long/slender fibers, short/coarse fibers, and fines, which can then be proportioned to different plies in the containerboard machine. Depending on the cleanliness of the recovered paper and the configuration of the particular stock preparation system, between 85% and 95% of the recovered paper can be used to produce recycled containerboard. Some recycled containerboard mills utilize a disperger, a device that heats dewatered stock to 80-110°C and applies mechanical energy to homogenize the pulp and its remaining contaminants. Other mills simply dewater the stock before the containerboard machine. All recycled containerboard mills reuse process water from the containerboard machine and the stock preparation dewatering equipment, resulting in significantly lower fresh water use per ton of containerboard produced than their fresh fiber counterparts.

Papermaking and Conversion

An overview of the papermaking process is shown in Figure 15.

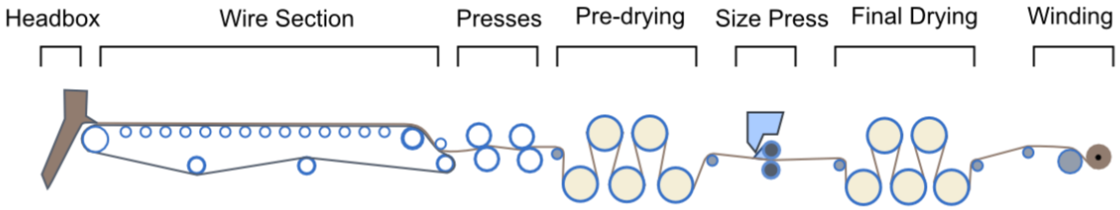

Figure 15. Papermaking Process

The pulp slurry, consisting of a desired blend of fresh fiber and recycled fibers, is fed into the headbox and distributed evenly across the width of the containerboard-making machine. Fed out from the headbox in a homogenous sheet onto "the wire," water contained in the slurry drains through as it moves along this mesh belt, either fed by gravity or aided by a slight vacuum, leaving the fibers behind. The pulp is further dried as it is pressed through felt rollers and then a series of steam-heated drying rollers; in this stage, the containerboard may also receive additions of starch or other surface coatings in the sizing press or presses, where the containerboard passes through rollers continually fed with the desired chemicals. Remaining moisture and any additional moisture picked up in the sizing press is dried in the after-dryers, before the containerboard is slit to size and rolled for delivery to further processing plants, specifically the converting plants, which make corrugated boxes and other corrugated products.

Supporting Activities

Supporting activities include on-site steam and power production, on-site chemical production, effluent treatment, on-site residual management, etc.

4.2.5 Converting

The rolls of linerboard and corrugating medium (two different types of containerboard) are shipped to converting plants, where they are first assembled into a sheet that combines both the linerboard and the medium, and then converted into the corrugated product. This is achieved by softening the medium through heat and steam treatment before receiving its distinctive fluted shape by being run through a pair of mating corrugated rollers. Starch is applied to the tips of the flutes and they are glued to the inner surface of one piece of linerboard. This initial board, with one layer of linerboard and one layer of corrugated medium (called singleface board), then passes on to the Double Backer, where starch is again applied and the flutes are glued to the second sheet of linerboard, making typical corrugated board (referred to as singlewall or doubleface). Further processing can add additional layers of corrugated medium and linerboard, building up double- or triple-walled board. The corrugated board is dried in the hot plate section, then slit into the required widths and cut into sheets, ready to be turned into boxes or other corrugated products. The final stages of processing (folding, gluing, and printing) are carried out and the finished products are stacked, palletized, and/or shipped.

As illustrated in Figure 16, three main types of converting facilities can be distinguished: corrugator plants, sheet feeder plants, and sheet plants. The ratio of corrugated product from corrugator and sheet plants was provided by CPA (Fibre Box Association 2015).

Corrugator plants assemble linerboard and corrugating medium into corrugated sheets, and convert sheets into corrugated products (e.g., boxes) at the same location. Some corrugator plants also act as sheet feeder or sheet plants. Sheet feeder plants assemble linerboard and corrugating medium into corrugated sheets and ship them for final conversion into boxes or other corrugated products, mostly to sheet plants but also, in some cases, to corrugator plants. Sheet plants convert corrugated sheets produced mainly in sheet feeder plants, but also in some corrugator plants, into corrugated products. For confidentiality reasons, it is not possible to provide life cycle inventory data for the three types of converting plants individually. Instead, one aggregated dataset is presented for the whole converting in Table 22. Note, however, that the same approach was used to model the 2010 and 2014 converting plants. More information on the converting plants in 2010 can be found in the report for the original study. Converting was modeled identically for both industry-average and 100%-recycled corrugated products.

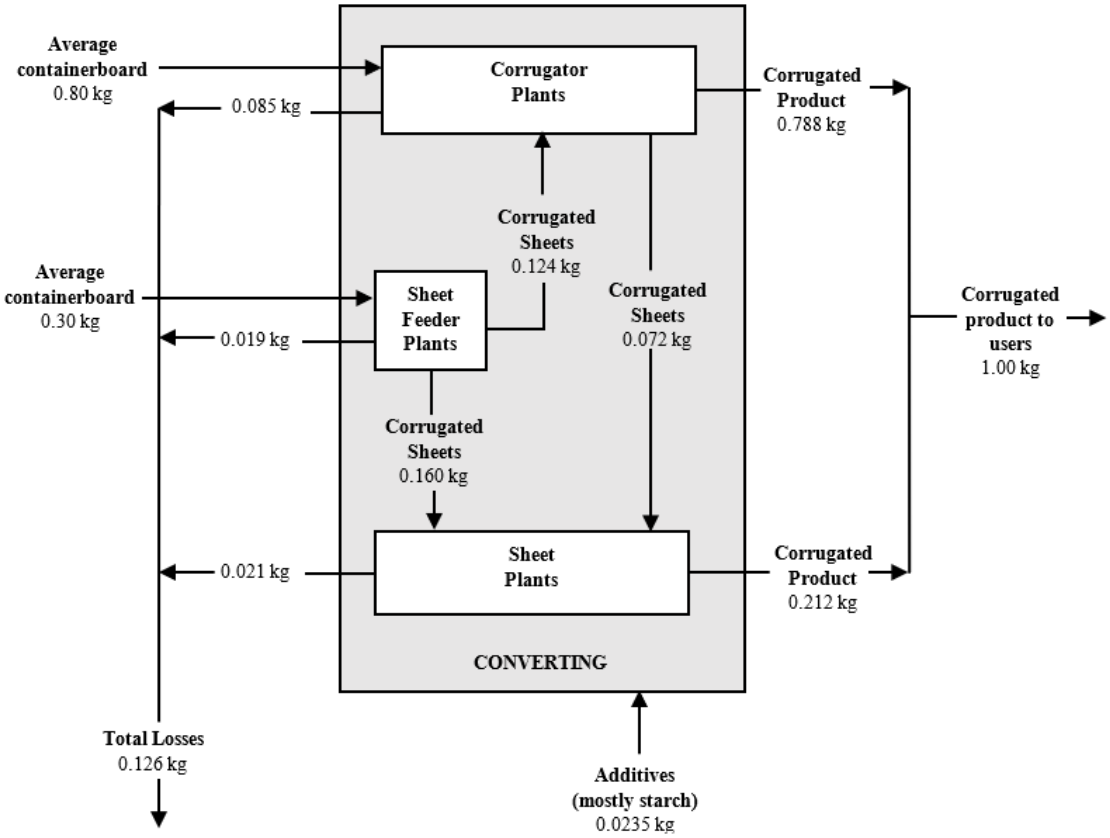

Figure 16. Overview of Converting Operations
[Note: Any differences between the figure above and the tables below are due to rounding.]

Table 22. Inputs/Outputs to Converting Unit Processes per Functional Unit (1.0 kg Corrugated Product)

Input/Output	Quantity	Unit[16]	Comment
INPUTS			
Resources			
Water intake	0.435	kg	
Fiber Raw Material			
Containerboard	1.10	kg	
Chemicals			
Starch	0.02	kg	
Wax	0.005	kg	
Ink	0.0003	kg	
Adhesive	0.002	kg	
Coating	3.9e-5	kg	
Borax	0.0003	kg	
Resin	0.0002	kg	
Caustic	0.0004	kg	
Energy			
Distillate fuel oil (#2)	3.97	MJ HHV	
Gasoline and kerosene	3.60e-5	MJ HHV	Modeled as 100% gasoline.
Liquid propane gas	0.050	MJ HHV	
Natural gas	1.26	MJ HHV	
Purchased power	0.142	kWh	
Purchased steam	0.001	MJ	
OUTPUTS			
Products and co-products			
Corrugated product	1.0	kg	
Emissions to air (process and combustion)			
Nitrogen oxides (NO_x)	2.0E-5	kg	
Sulfur oxides (SO_x)	2.8E-7	kg	
Particulates	9.5E-6	kg	
Carbon monoxide (CO)	4.51E-5	kg	
Carbon dioxide (CO_2), fossil	0.068	kg	
Methane (CH_4), fossil	1.23E-6	kg	
Nitrous oxide (N_2O)	2.28E-7	kg	
Non-methane VOCs	2.0E-5	kg	
Evaporated water	0.284	kg	Estimated by mass balances

(Table continued next page.)

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[16] All kg are dry kg.

Table 22. (Cont'd)

Input/Output	Quantity	Unit[17]	Comment
Emissions to air (Process specific and on-site fuel combustion			
Other toxics	As defined by the U.S. Toxics Release Inventory, estimated using U.S LCI data (NREL 2012)		
Emissions to water (direct releases refer to those directly released from converting facilities, while indirect means that it went through a third party).			
Effluent, direct	0.004	kg	
Effluent, indirect and other	0.150	kg	
BOD, direct	1.3E-10	kg	
TSS, direct	1.3E-10	kg	
Residuals			
Converting losses to recycling	0.125	kg	

4.2.6 Use

The "use" life cycle stage includes the use of corrugated products by various consumers. Because most environmental impacts arising during this life cycle stage would be allocated to the content of corrugated packaging, vs. the packaging itself, use-related impacts associated with the corrugated product were considered to be negligible, and thus are not included in the system boundary. This assumption was also made for the 2006 and 2010 studies. Transportation to the use phase is included in the system boundary. Carbon storage in use is also considered where applicable.

4.2.7 End-of-Life and Recovery

4.2.7.1 EoL Split

AF&PA started to report recycling rate as a 3-year average to eliminate potential large swings between annual numbers. In this LCA, we used the 3-year average with 2020 as the midpoint (i.e., average of 2019, 2020, and 2021), which is 90.5%. According to EPA (US EPA 2020a, Table 4), 80.3% of the non-recycled fraction was landfilled versus 19.7% burned in 2018, the most recent year for which data are available. Hence, the end-of-life split considered in this study was:

- Recycled: 90.5%;
- Combusted with energy recovery: 1.9%; and
- Landfilled: 7.6%.

The EoL was modeled the same way for the industry-average and 100%-recycled products.

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[17] All kg are dry kg.

4.2.7.2 Modeling Considerations

Landfill and incineration of OCC were modeled using secondary data that were modified to account for the actual carbon content of OCC considered in this study. In addition, the carbon balance around landfills was also modified to account for U.S.-specific conditions.

In landfills, a fraction of the biogenic carbon in forest products decays, primarily into gas. The remaining fraction, which varies by type of product, is non-degradable under anaerobic conditions. The degradable fraction of the biogenic carbon in landfills was assumed to decay according to a first-order equation as presented in Table 23. Under anaerobic conditions, about one-half of the carbon is converted to biogenic CO_2 while the other half is converted to CH_4. Under aerobic conditions (e.g., in shallow unmanaged landfills) a much smaller fraction of the gas consists of CH_4. A methane correction factor, provided in Table 23, was used to adjust methane generation to reflect the extent of anaerobic conditions in different types of landfills.

Another important factor influencing the releases of landfill CO_2 and methane (CH_4) to the atmosphere is the extent to which CH_4 is oxidized to biogenic CO_2 before exiting the landfill. Even in the absence of systems designed to capture and destroy methane, about 10% of the methane is oxidized as it moves through the surface layers of the landfill. Finally, some landfills are equipped with cover systems to collect and destroy methane by burning, and assumptions need to be made regarding the fraction of the methane that is collected and burned.

Landfill parameters used in this study are presented in Table 23.

Table 23. Parameters for Calculating Carbon Emissions from Landfilling of OCC

Parameter Analyzed	Value analyzed				Source(s)
	2020	2014	2010	2006	
Biogenic carbon content (CC)	49.4%	49.1%	49.5%	49.2%	Calculated.
Non-degradable carbon under anaerobic conditions (F_{CCND})	55%	55%	55%	55%	Wang et al. (2011)
Methane correction factor (MCF)	1	1	1	1	IPCC (2006b), methane correction factors set up to be representative of managed anaerobic conditions.
Fraction of methane oxidized in landfill covers (F_{CH4OX})	10%	10%	10%	10%	IPCC (2006b)
Fraction of methane burned (F_{CH4CB})	56%	53%	53%	53%	US EPA (2020b, Exhibit 6-11)

Cumulative quantities of carbon dioxide and methane emitted are calculated as follows.

Quantity of Carbon Converted to Gas at a Given Time:

$$Q_{C\rightarrow Gas} = Q_{CP} \times MCF \times CC \times (1 - F_{CCND})$$

Where Q_{CP} is the quantity of corrugated products sent to landfill.

Quantity of Carbon Converted to Methane ($Q_{C\text{->}CH4}$):

$$Q_{C\rightarrow CH4} = Q_{C\rightarrow Gas} \times 0.5$$

Quantity of Methane Not Collected and Burned (Q_{CH4NCB})

$$Q_{CH4NCB} = Q_{C\rightarrow CH4} \times (1 - F_{CH4CB})$$

Quantity of Methane Released to the Environment ($Q_{CH4,Landfill}$):

$$Q_{CH4,Landfill} = Q_{CH4NCB} \times (1 - F_{CH4OX}) \times \frac{16}{12}$$

Quantity of Carbon Dioxide Released to the Environment ($Q_{CO2,Landfill}$):

$$Q_{CO2,Landfill} = \left(Q_{C\rightarrow Gas} - Q_{CH4,landfill} \times \frac{12}{16}\right) \times \frac{44}{12}$$

4.2.8 Residuals Management

Management of the residues produced in the different life cycle stages, as well as their management mode, was discussed previously in Sections 3.5.2.3, 4.2.4.1 and 4.2.4.2 .

4.2.9 Transportation

Transportation distances were modeled using the 2017 Commodity Flow Survey (CFS) (U.S. Department of Transportation and U.S. Department of Commerce, 2020, Table 7) and the U.S. LCI database (NREL 2012), unless otherwise specified. More details are provided in Table 24. For data taken in the Commodity Flow Survey, multiple and unknown modes, as well as insignificant modes, were neglected. Data from the 2007 CFS (U.S. Department of Transportation and U.S. Department of Commerce & U.S. Department of Commerce, 2010) were used for 2006 and 2010. Reported distances are total traveled distances.

Table 24. Details of Transportation Modeling Assumptions

Material transported	Commodity Code	Assumed transportation profile							
		Truck		Train		Boat, Barge		Boat, Ocean	
		%	km	%	km	%	km	%	km
Wood logs to pulp and paper mills	SCTG#25	88.0	501	12.0	1270	0	0	0	0
Wood chips to pulp and paper mills	SCTG#26	96.0	249	4.0	1120	0	0	0	0
Recovered fiber to pulp and paper mills	SCTG#41	82.0	196	11.5	454	6.5	359	0	0
Pulp to pulp and paper mills	SCTG#27	89.0	309	11.0	1316	0	0	0	0
Chemicals	SCTG#20	63.0	488	15.0	1241	16.0	369	6.0	325
Containerboard to converting	SCTG#27	89.0	309	11.0	1316	0	0	0	0
Corrugated sheets	SCTG#27	89.0	309	11.0	1316	0	0	0	0
Corrugated product to use	SCTG#28	99.7	256	0	0	0.2	80	0.1	3067
Residuals to management and product to end-of life	SCTG#41	82.0	196	11.5	454	6.5	359	0	0
Purchased hogged fuel, other biomass	CORRIM (Johnson et al. 2012)	100	145	0	0	0	0	0	0
All other fuels	See U.S. LCI database								

While the SCTG#20 category is for basic chemicals only, and the system modeled uses various chemicals with various transportation profiles, the category was used as a simplification. Basic chemicals represent most of the chemical quantities used in the life cycle.

4.3 Calculation Procedures

The LCI and LCIA calculations were undertaken using the GaBi 10 software package[18] (Sphera Solutions Gmbh 2023).

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[18] Now sphere “LCA for Experts”.

4.4 Data Quality Assessment

Table 25 presents a qualitative assessment of the quality of the data used in this study (see Section 3.6 for a description of data quality requirements). As shown, most of the data used were of high quality. Where certain data of lesser quality were found to be significant to the results, they are discussed in the section on limitations of this study. In addition, representativeness was discussed in Section 3.2.

Table 25. Data Quality Assessment

Data required	**Reliability**	**Temporal correlation**	**Geographical correlation**	**Technological correlation**	**Representativeness Data collection**	**Process review**	**Process completeness**
	Score						
FOREGROUND SYSTEM – Containerboard production							
Material inputs	1-2	1	1	1	2	1	1
Air releases: Non-toxic	1-2	1	1	1	2	1	
Air releases: Toxic*	2	1	1	1	2 3 4-5	1	
Water releases, TN and TP	3	1	1	1	5	1	
Water releases: Non-toxic	1-2	1	1	1	2	1	
Water releases: Toxic	2	1	1	1	2 3 4-5	1	
Energy data	1-2	1	1	1	2	1	
Mill solid wastes and management	1-2	1	1	1	2	1	
Soil released	2	1	1	1	2 3 4-5	1	
Co-product quantity (e.g., turpentine)	4	1	1	1		1	
All data	1-2	1	1	1	4	1	1

(Table continued next page. See note at end of table.)

Table 25. (Cont'd)

Data required	Reliability	Temporal correlation	Geographical correlation	Technological correlation	Representativeness Data collection	Process review	Process completeness
	Score						
BACKGROUND SYSTEM							
Forest operations	2	1-2	1	1 3	1-2 3 4-5	3	5
Chip production	2	1-2	1 🟨	1 3	1-2 3 4-5	3	
Chemical production	1-2 3 4-5	1-2 3	1-2 5	3 4-5	1-2 3 4-5	1-2 3 5	
Electricity production	1-2	1	1	1 3	1-2 3 4-5	1-2 3 5	
End-of-life, split	1	1	1	1	1-2 3 4-5	1-2 3 5	
End-of-life, models	1-2	1	5	1	1-2 3 4-5	1-2 3 5	
TRANSPORTATION							
Distances and modes	1-2	2	1	3	5	3	5
Transportation processes	1-2	2 3	1	5	5	3	

NOTE: The data quality assessment presented in this table is based on a new method by U.S. EPA (Edelen and Ingwerse 2016). Although this method is more stringent than that applied in previous studies (Weidema et al. 2013), overall data quality is similar to that in prior years.

5. LIFE CYCLE IMPACT ASSESSMENT METHODS

5.1 General LCIA Methods

According to ISO 14044, the mandatory elements of LCIA include (1) the selection of impact categories, category indicators, and characterization models; (2) the assignment of LCI results to the selected impact categories (classification); and (3) the calculation of category indicator results (characterization). LCIA can also include optional elements (normalization, grouping, and weighting). The ISO 14047 Technical Report (ISO 2012a) provides a list of commonly-used impact categories: global warming, stratospheric ozone depletion, photo-oxidant formation, acidification, nitrification (eutrophication), human toxicity, ecotoxicity, depletion of abiotic resources, and depletion of biotic resources. ISO recognizes that this list is not exhaustive. Other categories may look at radiation, noise and odor, or land use[19], but for these latter categories, no widely-accepted characterization methods are yet available.

This study used the TRACI LCIA method (Bare et al. 2003) for impact assessment and the CML method (Guinee et al. 2002) as a sensitivity analysis. The most recent versions of these methods, as implemented in GaBi, were used (i.e., TRACI 2.1 (2012) and CML 2001 updated in August 2016). The CML method was used only for those indicators that have an equivalent in TRACI. The TRACI and CML methods have their own lists of impact categories. Table 26 links TRACI and CML impact categories with those listed in the ISO 14047 Technical Report, indicating those considered in this study. Other methods were also used as appropriate. For instance, information of global warming potentials was derived from the Sixth Assessment Report (AR6). Impacts on land use and biodiversity were not quantified as there is no consensus method suitable for forest management.

Additional results are also presented for indicators at the inventory level: primary energy demand (non-renewable and renewable) and water use and water consumption. Turbine and rainwater were not included within water use.

Because some of the impact factors have been updated since 2014, impact scores were recalculated for the three previous LCA study years in making the comparison.

The ISO 14044 Standard also requires that, for comparative assertions, the report include a statement as to whether international acceptance exists for the selected category indicators. The only international evaluation of existing category indicators can be found in the ILCD Handbook (European Comission - Joint Research Centre - Institute for Environment and Sustainability 2011) and is specific to the European context. Nonetheless, this document was used as the basis for evaluating the international acceptance of the category indicators used in this study, as presented in Table 27. The inventory indicators are not presented in this table.

No grouping, normalization, or weighting were performed.

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[19] Land use impact assessment methodologies are still under development. Inventory numbers are difficult to interpret and, without accepted impact assessment methodologies, could easily be misused and/or misinterpreted. For these reasons, land use numbers are not presented in this report.

Table 26. Selected Methods for LCA Impact Categories

Impact categories proposed by ISO 14047	**TRACI 2.1 (2012) method**		**CML 2001 method**		**Other Method**	
	Indicator name	**Indicator results (unit)**	**Indicator name**	**Indicator results (unit)**	**Indicator name**	**Indicator results (unit)**
Climate change	TRACI indicator not used.		CML indicator not used.		Global warming* IPCC AR6	kg CO_2 eq.[20]
Stratospheric ozone depletion	Ozone depletion (1999 World Meteorological Organization, WMO, model)	kg CFC-11 eq.	N/A (same model implemented in TRACI and CML)		N/A	
Photo-oxidant formation	Smog	kg O_3 eq.	Photochemical oxidation	kg C_2H_4 eq.	N/A	
Acidification	Acidification (water and air)	kg SO_2 eq.	Acidification	kg SO_2 eq.	N/A	
Nitrification/ Eutrophication	Eutrophication (water and air)	kg N eq.	Eutrophication (water and soil)	kg PO_4 eq.	N/A	
Human toxicity†	Carcinogenics	CTUh	N/A.		N/A	
	Non carcinogenics	CTUh			N/A	
Ecotoxicity†	Ecotoxicity	CTUe			N/A	
					N/A	
					N/A	
Depletion of abiotic resources (e.g., fossil fuels, minerals)‡	Fossil fuel depletion	MJ surplus	The CML “abiotic resource depletion” indicator will not be included because there is no equivalent in TRACI. Factors for fossil fuel depletion were not used.		Primary energy demand (non-renewable, gross) - GaBi	MJ
Depletion of biotic resources (e.g., fish, wood)	No indicator is available in TRACI or in CML.				Primary energy demand (renewable, gross) - GaBi	MJ
Land use impacts	Neither TRACI nor CML provides an indicator for land use. Impact assessment methodologies are still under development and inventory numbers are difficult to interpret without generally accepted impact assessment methodologies and could easily be misused					
Respiratory effects inorganics substances§	Respiratory effects RE	kg PM2.5 eq.	N/A.		N/A	

**In this report, "global warming" is used instead of "climate change". †Toxicity-related impact categories were excluded from the original study because of their inherent uncertainty However, recently, the USEtox method, which represents a consensus amongst several life cycle impact assessment researchers, was published (Rosenbaum et al. 2008) and incorporated within TRACI. The results from applying this method are provided in Appendix* H *as a learning experience. ‡ The primary energy demand (GaBi) evaluates the total energy requirements throughout the life cycle of the studied product. The fossil fuel depletion indicator (TRACI) accounts for the fact that continued extraction and production of fossil fuels tend to consume the most economically recoverable reserves first so that continued extraction will become more energy intensive in the future (Bare et al. 2003). The fossil fuel depletion indicator is an attempt to estimate the incremental energy requirements per unit of consumption of fuel in the future compared to today’s conditions. §Mentioned in ISO 14047, but not described as commonly used.*

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[20] Equivalents.

Table 27. Evaluation of International Acceptance of the Category Indicators Used

Impact categories	Evaluation of international acceptance*
Global warming (GW)	There is a wide consensus on the use of IPCC's global warming potentials.
Ozone depletion (ODP)	There is a wide consensus on the uses of the World Meteorological Organisation's ozone depletion potentials that are implemented in all LCIA method.
Smog (POCP)	The ILCD Handbook makes the following evaluation of TRACI's smog indicator: *"weighted towards human health impacts (?). Fate model extensively reviewed, further components derived from reviewed information, no treatment of uncertainty in resulting CFs**. Method principles and CFs documented and accessible for app. 580 substances."*
Acidification (AP)	The ILCD Handbook makes the following evaluation of TRACI's acidification indicator: *"The method lacks of sufficient environmental relevance. It fully considers atmospheric fate, but not the soil sensitivity to acidifying deposition. It needs to be at least complemented by average soil fate factors distinguishing for sensitive and non-sensitive areas"*. The results obtained for the acidification indicator in this study were compared with those using CML that meets the ILCD Handbook science criteria. The use of one method versus the other did not affect the results significantly.
Eutrophication (EP)	The ILCD Handbook makes the following evaluation of TRACI's eutrophication indicator (aquatic only): "*Fate model well reviewed, but NH3not covered. Further components derived from reviewed information, some treatment of spatially determined uncertainty in resulting CFs. Method principles and CFs documented and accessible for all main contributing substances."* The CFs for the terrestrial eutrophication were published after the evaluation by the European Commission. Also, NH_3 is now included in TRACI.
Human toxicity and ecotoxicity (HHC/ECO)	The USETox model is the LCIA method recommended by the ILCD Handbook in the European context. A U.S.-specific version of that method (in TRACI) was used. However, the ILCD Handbook specifies that it needs some improvement and should be used with caution. For this reason, the method was not used to perform any comparison.
Fossil fuel depletion (FF)	TRACI's FF impact category is based on EcoIndicator. The ILCD evaluation of the EcoIndicator resource depletion indicator is as follows: *"Relatively simple model, based on estimated slope factors. Combination with fossil fuels somewhat problematic."* The use of fossil fuels was also characterized using a non-renewable primary energy inventory indicator that generally led to similar conclusions.
Respiratory effects (RES)	TRACI method for respiratory effects was described as *"good science based"* by the ILCD Handbook.

**Note: The evaluation of the ILCD Handbook was based on a previous version of the TRACI method but is still mostly applicable. **CFs: Characterization factors.*

5.2 Accounting Practices for Biogenic Greenhouse Gases and Land Use Change

5.2.1 Flow and Stock Change Accounting for Biogenic CO_2

In accordance with accepted greenhouse gas accounting practices, biomass-derived CO_2 was tracked separately from fossil fuel-derived CO_2 and other greenhouse gases in the life cycle inventory. There are two main approaches for biogenic carbon accounting (IPCC 2006a, NCASI 2013b): flow accounting and stock change accounting.

Although typically not referred to using this terminology in LCA studies, **flow accounting** is the approach most commonly used in LCA. This approach consists of characterizing the effects of biomass carbon on the atmosphere by calculating the net emissions of biogenic CO_2 (emissions minus removals) occurring in the product system, which are then added to the global warming results. This approach was used in the previous containerboard LCA studies and is also used in this study. In applying this approach, the same GWP was applied to methane releases from biogenic and fossil sources to avoid double counting the removal.[21]

Stock change accounting is typically used in national inventories. This approach characterizes the effects of biomass carbon on global warming by calculating the changes in the stocks of stored carbon through the life cycle of the product. An increase in stocks is beneficial for the global warming indicator and a decrease in stocks is detrimental for the global warming indicator. Note that stock change accounting leads to similar results as those using the approach recommended in ISO 21930, which consists of using a flow accounting approach in which inputs of recycled fiber comes in the system with an attached carbon removal and where outputs of recycled fiber are modeled assuming the carbon in the fiber returns to the environment.

In systems where there are no flows of stored biogenic carbon (e.g., carbon in wood fiber) across system boundaries, the net change in total stocks of stored biomass carbon is mathematically equal to the net flow of biomass carbon to/from the atmosphere, i.e., what is stored is not released. Flows of stored biomass carbon across system boundaries are mostly related to recycling. Indeed, for all products in this study there is a net export of old corrugated containers to other product systems. As a consequence of that export, the calculated global warming impact from biomass carbon depends on the accounting approach used (see Figure 48 and Figure 49 in Appendix B for cradle-to-grave schematics of carbon flows and stocks). Because of the potential differences in global warming results caused by the accounting approach, it was decided to present the stock change results as a sensitivity analysis. In using this approach, a GWP for biogenic methane lower than that from fossil sources was applied, as recommended by IPCC.

Another approach sometimes used in LCA is simply ignoring biogenic CO_2 when calculating the global warming indicator results (see examples in NCASI 2011) to obtain an understanding of how non-biogenic CO_2 GHG contribute to the global warming indicator. Note that this approach ignores any removal/storage of biogenic carbon.

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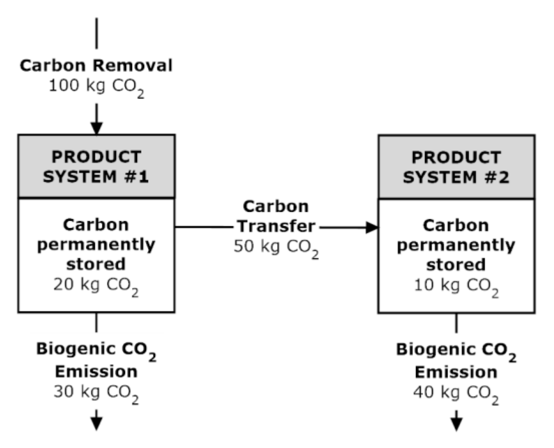
[21] IPCC (2013, Table 8.A.1) proposes two different GWPs for methane: one for fossil (30 kg CO_2 eq./kg) and one for biogenic (28 kg CO_2 eq./kg). However, as highlighted by IPPC, caution is needed in applying these potentials to avoid any double-counting. When applying the flow accounting method, CO_2 taken up by the biosphere then released as methane is already accounted for by the removal.



	Flow accounting	**Stock change accounting**	**Ignoring biogenic CO_2**
Product system #1 (GW_{P1})	-100 + 30 = -70 kg CO_2	-20 kg CO_2	0
Product system #2 (GW_{P2})	40 kg CO_2	-10 kg CO_2	0
$GW_{P1} + GW_{P2}$	-30 kg CO_2	-30 kg CO_2	0
Net flow of biogenic CO_2 ($NetBioCO2_{P1+P2}$)	-30 kg CO_2		
$GW_{P1} + GW_{P2} - GW_{P1+P2}$	0	0	30 kg CO_2

Figure 17. Illustration of Various Biogenic Carbon Accounting Methods

(Note: The example in the figure above applies a Cut-Off Method for recycling, meaning that the environmental load is applied where it occurs. However, the approach is equally valid for other allocation methods for recycling. For instance, if one was to apply the flow accounting method to biogenic carbon and the Number of Uses Method for recycling, a fraction of the net biogenic carbon flow in Product System #1 (i.e., -100 + 30) would have been transferred to Product System #2. Similarly, if the stock change accounting method was used, a fraction of the fraction permanently stored in Product System #1 (20) would have been transferred to Product System #2 if the Number of Uses Method was applied.

5.2.2 Change in Stocks Potentially Occurring in a Forest Product Life Cycle

Understanding where stock changes occur in the life cycle of a forest product is necessary for using stock change accounting and is useful in interpreting biogenic CO_2 emissions information generated by both stock change and flow accounting. There are three main places where a change in carbon stocks can occur in a forest product life cycle: in the forest, in use, and in landfills. These are discussed in greater detail next.

5.2.2.1 Forest Carbon Stocks

Where forests are managed to produce a sustained yield of fiber, changes in forest carbon stocks mostly occur through land use changes (e.g., through forest conversion to a different land use), although forest carbon stocks can increase or decrease without changing the land use type (e.g., where high-carbon stock forests are converted to intensively-managed forests).

Capturing impacts of land use change or change in forest carbon stocks on GHGs in LCA studies is always challenging, especially when performing an assessment at the scale of the entire industry. Data do not exist that would allow a detailed assessment of the impacts of each containerboard mill on forest carbon stocks. We are left, therefore, with having to assess potential impacts at a larger scale. The WRI/WBCSD Product Standard suggests just such an approach when the specific land supplying wood cannot be identified (WRI and WBCSD 2011b).

A report by U.S. EPA shows that forest area and related carbon stocks in the U.S. are stable to increasing between 1990 and 2020 (U.S. EPA 2022, Table 6-10). This finding is conceptually consistent with adherence to sustainable forest management certification principles (a requirement of AF&PA membership), which require regeneration of the forest to meet future needs for wood. With forest carbon stocks stable or increasing, it follows that the carbon being removed from these forests by harvesting, fires, and other means is being offset (or more) by growth in the forest, representing net flows of carbon into the forest from the atmosphere. These observations are used to support assumptions about the flows of CO_2 into forests that provide wood to the containerboard sector (i.e., it is assumed that the carbon in the wood removed for containerboard is equal to the carbon removed from the atmosphere by that system).

Furthermore, several studies (e.g., Abt et al. 2012, Daigneault et al. 2012) have shown that where forest is being lost it is not due to use of the land for wood production. Indeed, research demonstrates that the market for wood in the U.S. helps avoid conversion of forest to other non-forest uses (e.g., Galik and Abt 2012, Hardie et al. 2000, Lubowski et al. 2008).

Therefore, based on empirical evidence of (a) stable (or increasing) forest carbon stocks, (b) increasing forested area, and (c) research demonstrating that the demand for wood helps counteract deforestation, it was assumed that there was no change in forest carbon stocks attributable to wood harvested to make containerboard. In addition, although the carbon stocks are slightly increasing, no credits for these additional removals were considered in this study.

5.2.2.2 In Use Carbon Stocks

When forest products remain in circulation for a long period, for instance more than 100 years, this is sometimes considered as an increase in carbon stocks (Miner 2006). In this study, an infinite period of time was selected as a temporal boundary; hence, no storage of carbon in products in use was considered. The potential effect of this choice on the results was evaluated by calculating the amounts of biomass carbon in products in use expected to remain out of the atmosphere for at least 100 years (as this represents a long-term net removal of carbon from the atmosphere).

5.2.2.3 Landfill Carbon Stocks

When products are sent to landfill a fraction of their carbon is non-degradable and hence the stocks of carbon in landfills are increasing. Additions to carbon stocks in landfills were assumed to be equal to the amount of biomass carbon in the product that is non-degradable under anaerobic conditions. The modeling details for landfills can be found in Section 4.2.7.2.

5.2.3 Biogenic CH_4 and N_2O

In this study, IPCC AR6 GWPs were used to calculate the global warming indicator results. As required by IPCC and other major greenhouse gas accounting protocols (WRI and WBCSD 2004), where methane or nitrous oxide are formed in biomass combustion these were included in fossil fuel-derived greenhouse gas totals and the IPCC AR6 factors were applied.

5.2.4 Summary of Biogenic GHG Approach

In summary, for calculating the global warming indicator results, IPCC AR6 global warming potentials and flow accounting were used. Using that approach, the global warming results were calculated as follows:

$$GW,F = GW_{FF} + (E_{BioCO2} - R_{BioCO2}) \times 1 + CH_{4,Bio} \times 29.8 + N_2O_{Bio} \times 273 + E_{FC}$$

Where GW,F is the global warming results calculated using flow accounting for biogenic CO_2 (in kg CO_2 eq.); GW_{FF}, is the global warming from fossil fuels; E_{BioCO2}, the emissions of biogenic CO_2 (in kg); R_{BioCO2}, the removals (in kg); CH_{4Bio}, the methane emissions from biomass (in kg); N_2O_{Bio}, the emissions of nitrous oxide (in kg); 1, 29.8, and 273 the GWPs for CO_2, CH_4 and N_2O (in kg CO_2 eq./kg); and E_{FC}, the emissions due to change in forest carbon stocks (in kg CO_2 eq.). E_{FC} was assumed to be 0.

Stock change accounting was used as a sensitivity analysis. Using that approach, the global warming results were calculated as follows:

$$GW,S = GW_{FF} + CH_{4,Bio} \times 27 + N_2O_{Bio} \times 273 - S_1 - S_2 - S_3$$

Where GW,S is the global warming results calculated using stock change accounting for biogenic CO_2 (in kg CO_2 eq.); GW_{FF}, is the global warming from fossil fuels; S_1, the change in forest carbon stocks (in kg CO_2 eq.); S_2, the change in "in use" stocks (in kg CO_2 eq.) and S_3, the change in landfill stocks (in kg CO_2 eq.). S_1 and S_2 were assumed to be 0.

More details regarding flows of biogenic carbon in the product systems analyzed can be found in Appendix B.

6. RESULTS AND INTERPRETATION: 2020 LCA

6.1 LCIA and Additional Indicator Results

This section presents the results for the impact categories and inventory indicators specified above. All these results, unless otherwise specified, are based on the 2020 actual dataset. Note that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. LCIA indicator results are presented in Table 28 and inventory indicators in Table 29. More details are presented in subsequent sections of this report. Toxicity indicator results are presented in Appendix H.

Table 28. LCIA Indicator Results per Functional Unit (Industry-Average)

Impact categories proposed by ISO 14047	Nomenclature	TRACI method	CML method	IPCC AR6 GWPs
Global warming				
Flow accounting	GW,F			0.414 kg CO$_2$ eq.
Stock change accounting (sensitivity analysis)	*GW,S*			*1.26 kg CO$_2$ eq.*
Excluding biogenic CO$_2$ (sensitivity analysis)	*GW,Excl. BioCO$_2$*			*1.36 kg CO$_2$ eq.*
Stratospheric ozone depletion	ODP	6.22E-8 kg CFC-11 eq.		
Photo-oxidant formation	POCP	0.090 kg O$_3$ eq.	7.83E-4 kg C$_2$H$_4$ eq.	
Acidification	AP	8.73E-3 kg SO$_2$ eq.*	8.90E-3 kg SO$_2$ eq.	
Nitrification/ Eutrophication	EP	9.27E-4 kg N eq.*	9.02E-4 kg PO$_4$ eq.	
Depletion of abiotic resources (e.g., fossil fuels, minerals)	FF	2.17 MJ surplus		
Respiratory effects inorganics	RES	7.17E-4 kg PM2.5 eq.		

**Total of air and water.*

Table 29. LCI Indicator Results per Functional Unit (Industry-Average)

Additional indicator	Nomenclature	Results
Non-renewable primary energy demand	NRPE	23.42
Renewable primary energy demand[22]	RPE	18.27
Water use	WU	43.37
Water consumption	WC	10.59

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[22] Excluding feedstock.

6.2 Identification of Significant Issues

According to the ISO 14044 Standard, the objective of "identification of significant issues" element of an LCA is to structure the results from the LCI or LCIA phases to determine what is important to the result. Different methods exist to identify significant issues; contribution analyses are the most commonly used. In contribution analyses, the contribution of life cycle stages or groups of unit processes to the total result is examined. In addition, the contribution of individual inventory parameters to different impact categories can also be analyzed.

Contribution analyses are presented in Figure 18, Figure 19 and Figure 20. These figures show that the pulp and papermaking operations life cycle stage, which includes forestry operations, is the main contributor to all indicators except global warming, to which it contributes negatively (i.e., accomplishes net removals of CO_2 from the atmosphere). The converting life cycle stage is a significant contributor to all indicators. End-of-life is relevant only for the global warming indicator.

Results depicted in Figure 20 also show that the choice of method for calculating the various indicators has little effect in terms of how each life-cycle stage contributes to the impacts.

Each indicator is discussed in greater detail below, with a focus on the global warming indicator. Although the CML method was applied only as a sensitivity analysis, the results of applying this method are discussed directly for each indicator, where applicable, instead of in the sensitivity analysis section of the report.

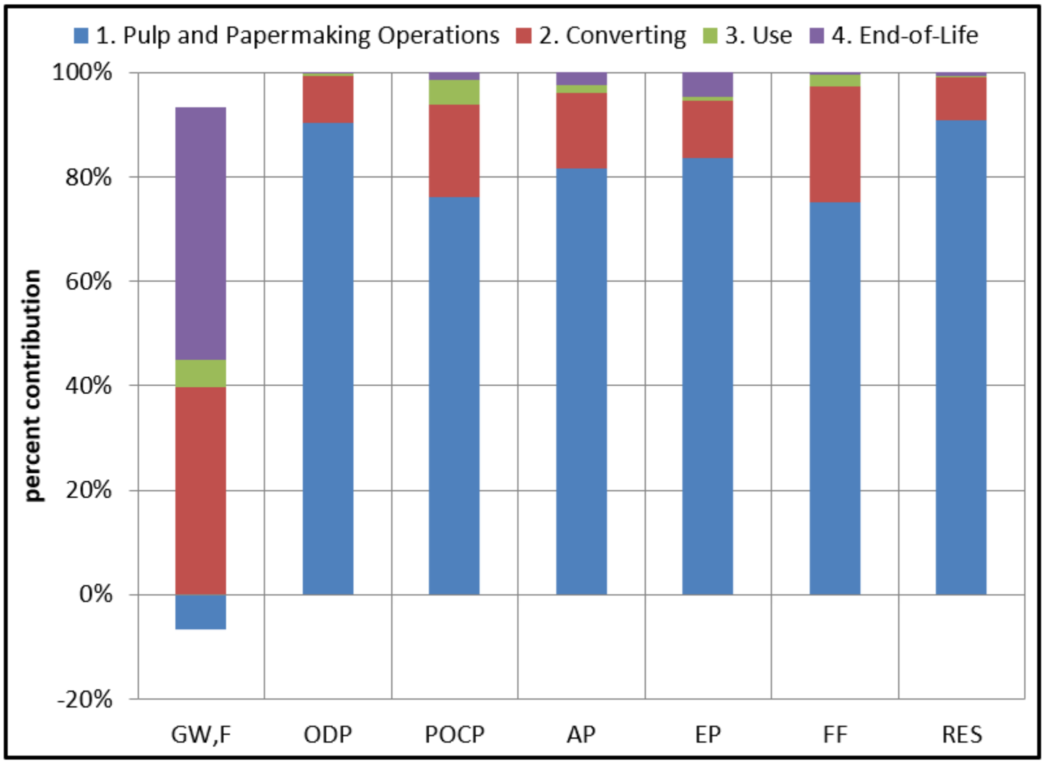


Figure 18. Contribution Analyses for LCIA Indicators, TRACI and IPCC (Industry-Average)

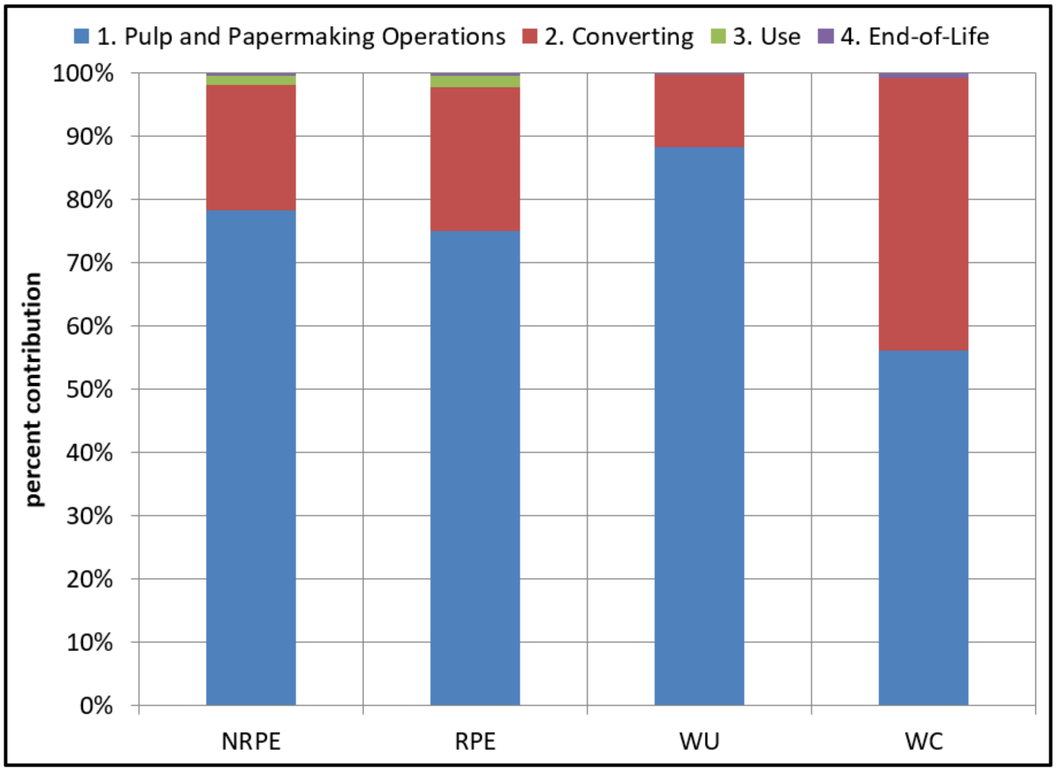


Figure 19. Contribution Analyses for LCI Indicators, GaBi and Inventory (Industry-Average)

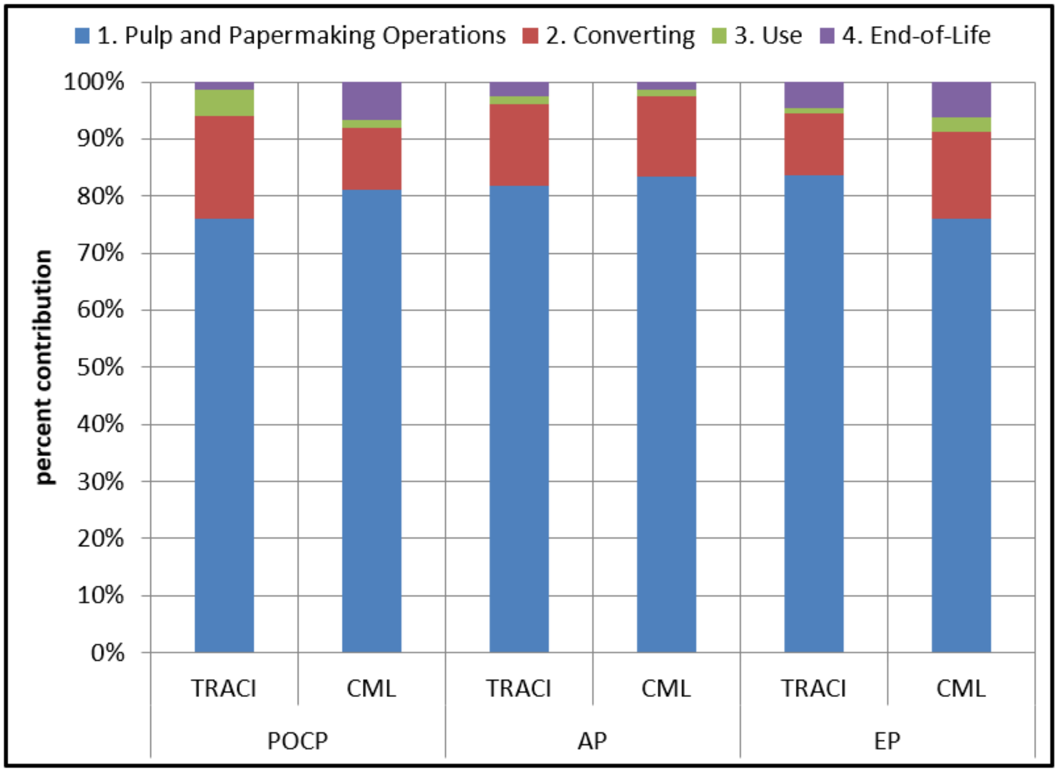


Figure 20. Contribution Analyses for LCIA Indicators, CML Method (Industry-Average)

6.2.1 Global Warming

This section presents more details on the global warming indicator.

Figure 21 presents the global warming indicator using different approaches for biogenic CO_2. It shows that the flow accounting method gives lower results than alternative approaches (i.e., the stock accounting method and excluding biogenic CO_2). This is because there is a significant amount of carbon removed from the atmosphere (negative emission of GHG) that is accounted for using the flow accounting method. This also explains why the pulp and paper making operations life cycle stages show little contribution to the global warming indicator using the flow accounting method. Indeed, using this method, removals of carbon that occur within the life cycle stage (trees growing in the forest) are enough to offset other emissions from this life cycle stage.

Figure 21 also shows that the reported values for the stock change accounting method are lower than when totally ignoring biogenic CO_2. This is explained by the fact that some biogenic carbon is stored (negative emission) within the system boundaries of the product investigated and this is accounted for using the stock change accounting method but not when ignoring biogenic CO_2.

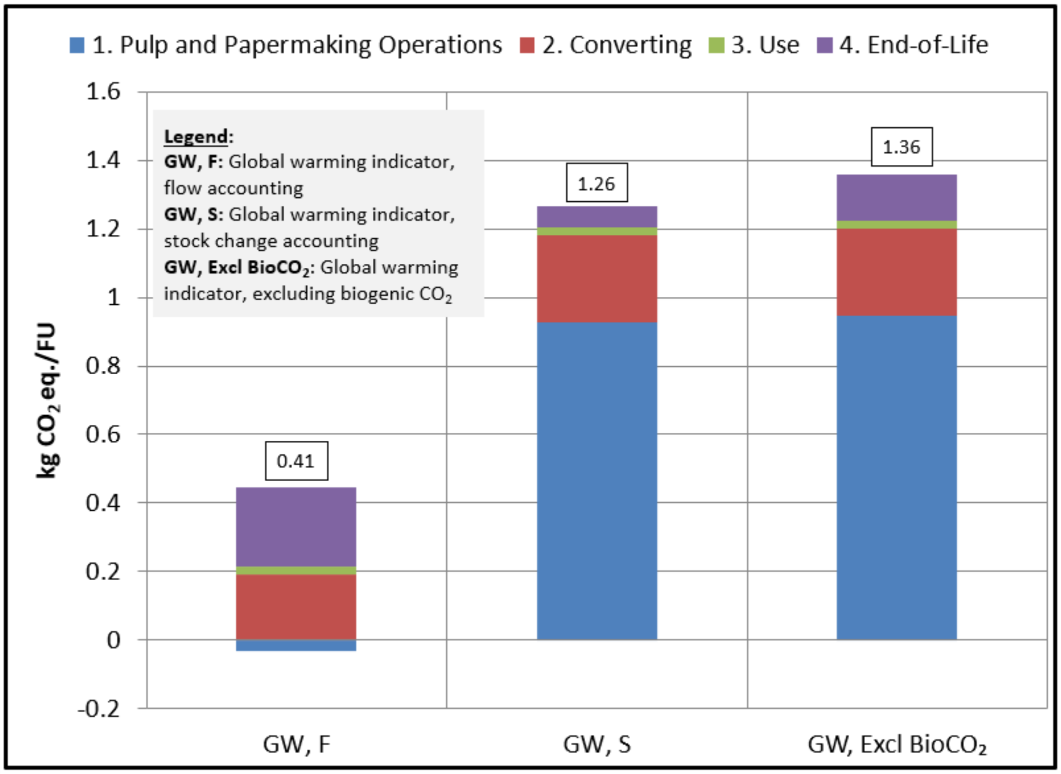


Figure 21. Global Warming Results

Table 30 details the contribution of the life cycle stages and some groups of unit processes to each of the GHGs that contributes towards the global warming indicator (flow accounting method). Figure 22 presents visually how each life cycle stage contributes to the individual GHGs and drills down into the pulp and papermaking operations and converting life cycle stages.

The following can be observed from Table 30 and Figure 22a:

- Removals (primarily due to biomass grown to produce containerboard) offset a large proportion of all GHGs (biogenic CO_2 and other GHGs).
- Emissions of biogenic CO_2 occur mainly at in the pulp and papermaking operations life-cycle stage.
- Emissions of other GHGs are distributed across the pulp and papermaking operations, converting, and end-of-life life cycle stages.
- Overall, the main contributors to the total global warming indicator are end-of-life and converting.

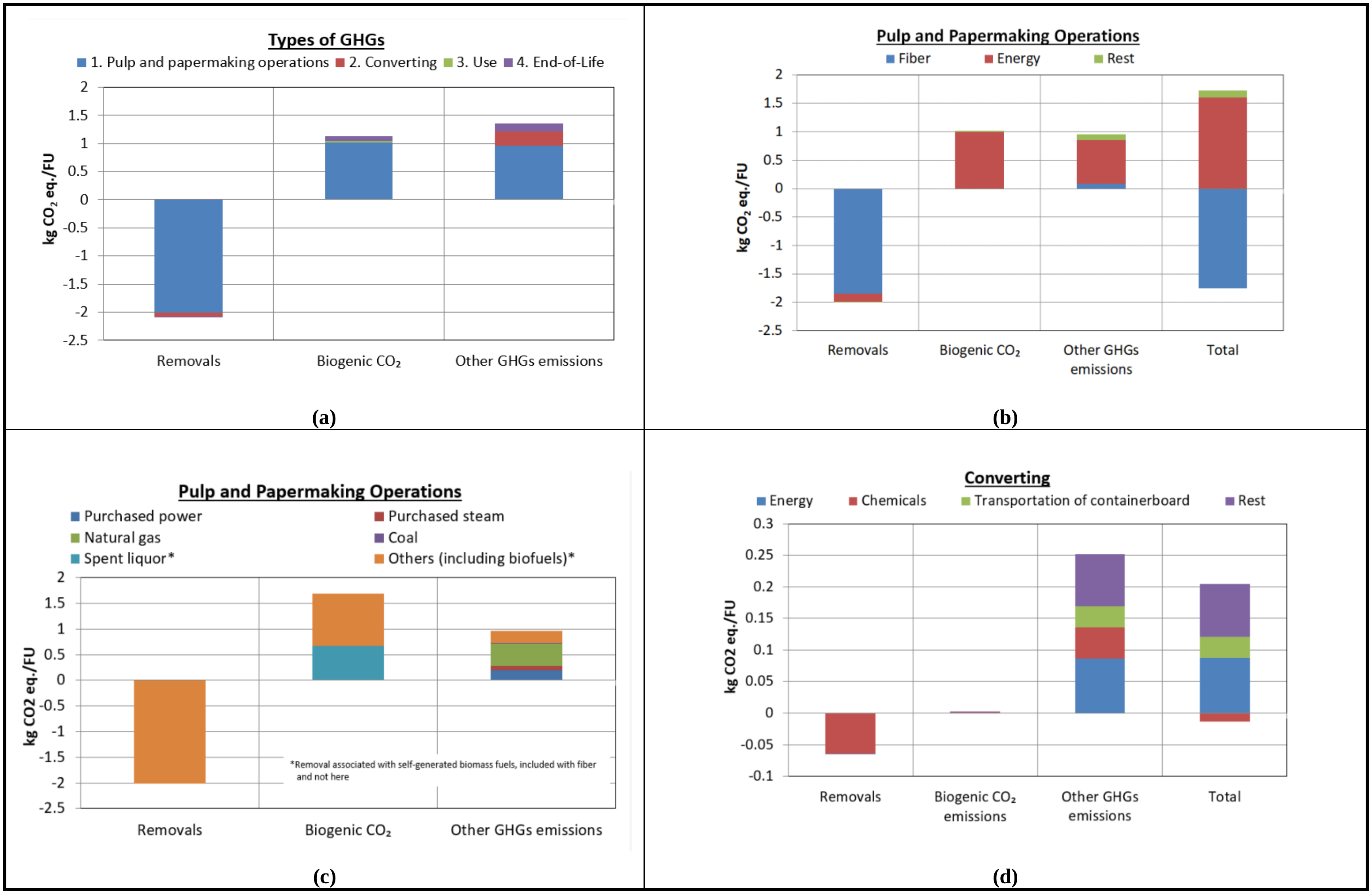
Figure 22b shows that, within the pulp and papermaking operations life cycle stage, forest operations are responsible for most removals while energy production is mainly responsible for biogenic CO_2 and other GHG emissions. The remaining life cycle stages, for instance chemical production and residual management, do not contribute significantly to the global warming indicator. Figure 22c presents the contributions of various energy sources to the individual GHG and total global warming indicator results. Biofuels such as spent liquor and hogged fuel are the only significant contributors to biogenic CO_2. Note that in Figure 22c, only a small portion of the removals is depicted. This is because the removals associated with spent liquor and self-generated hogged fuel are accounted for with the fiber input. Other GHGs are distributed across various energy sources including, in order of contribution, purchased power, natural gas, coal, and purchased steam. Figure 22d focuses on converting. From this figure, the following can be observed:

- Chemicals (starch) are responsible for the removals.
- There are very low emissions of biogenic CO_2 because converting facilities do not typically utilize biomass fuels for energy generation.
- Other GHGs are spread across energy (mainly purchased electricity and natural gas), transportation of the containerboard to converting facilities, and chemicals (mainly starch and ink), with energy being the main contributor to the total global warming impact score.

Table 30. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Global Warming Results by Type of Gases (Industry-Average)

Life cycle stage/Unit process		**Removals**	**Biogenic CO_2 emissions**	**Other GHGs emissions**	**Total**
		kg CO_2 eq./FU			
1. Pulp and papermaking operations		-2.01	1.02	0.96	-0.032
	Fiber	-1.85	0.00	0.09	-1.76
	Energy	-0.15	0.99	0.76	1.60
	Rest	-0.01	0.03	0.11	0.12
2. Converting		-0.06	0.00	0.25	0.19
	Energy	0.00	0.00	0.09	0.09
	Chemicals	-0.06	0.00	0.05	-0.01
	Transportation of containerboard	0.00	0.00	0.03	0.03
	Rest	0.00	0.00	0.08	0.08
3. Use		0.00	0.02	0.00	0.02
4. End-of-Life		0.00	0.08	0.15	0.23
Total		***-2.07***	***1.13***	***1.36***	***0.41***

NOTE: In this table, the main individual contributors are displayed in yellow.



(a)

(b)

(c)

(d)

Figure 22. Detailed Contribution Analyses for the Global Warming Indicator a) Type of Gases b) Pulp and Papermaking Operations, c) Energy used at Pulp and Papermaking Operations, and d) Converting (Industry-Average)

Table 31 presents the cradle-to-gate carbon footprint results for 1 kg of containerboard and 1 kg of corrugated product.

Table 31. Cradle-to-Gate Carbon Footprint for the Industry-Average Product

Product	**Flow accounting**				**Stock change accounting**	**Excluding biogenic CO_2[a, b]**
	Non-biogenic CO_2 GHGs[a]	**Biogenic CO_2**	**Biogenic removal**	**Net**		
	kg CO_2 eq./kg					
Industry-Average containerboard	0.87	0.93	-1.83	-0.029	0.85	0.87
Industry-Average corrugated product	1.21	1.02	-2.07	0.16	1.18	1.20

[a] Refers to fossil GHGs and other non-CO_2 biogenic GHGs. Value typically needed for "purchased goods and services" in GHG reporting and needed for third-party Environmental Product Declarations (EPDs). NOTE: For flow accounting, the GWP of CH_4 is 29.8 kg CO_2 eq./kg. For stock change accounting and accounting that excludes biogenic CO_2, the GWP of CH_4 is 27 kg CO_2 eq./kg.

6.2.2 Ozone Depletion

Table 32 details the contribution of the life cycle stages and some groups of unit processes to each substance that contributes towards the ozone depletion indicator. In this table, the five main contributors are highlighted in yellow. Note that energy used at pulp and paper mills is the main contributor. More specifically:

- chloromethane is mostly released through spent liquor combustion at pulp and paper mills;
- methyl bromide and 1,1,1-trichloroethane are mostly released through wood combustion at pulp and paper mills; and
- halon 1211 is mostly released through natural gas combustion both at pulp and paper and power plants.

Table 32. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Ozone Depletion Results by Substances (Industry-Average)

Life cycle stage/ Unit process	**Chloromethane**	**Methyl Bromide**	**Halon 1211**	**1,1,1-trichloroethane**	**Others**	**Total**
Total	6.6%	25.9%	42.8%	21.0%	3.7%	100%
1. Pulp and papermaking operations	6.5%	24.8%	35.2%	21.0%	2.9%	90.4%
Fiber	0.4%	0.0%	2.1%	0.0%	0.3%	2.7%
Energy	6.1%	24.8%	32.6%	16.7%	2.6%	82.8%
Process emissions and others	0.0%	0.0%	0.4%	4.3%	0.0%	4.8%
2. Converting	0.1%	1.1%	6.9%	0.0%	0.8%	8.9%
3. Use	0.0%	0.0%	0.6%	0.0%	0.0%	0.7%
4. End-of-Life	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%

NOTE: In this table, the main individual contributors are displayed in yellow.

6.2.3 Photo-Oxidant Formation (Smog)

Table 33 shows that, using the TRACI method, NO_x is the main substance relevant to the smog indicator, with the pulp and papermaking operations as its main contributor. The main processes contributing to NO_x are highlighted in yellow. Various forms of energy used at pulp and paper mills, including wood fuels, coal, or purchased power, cause a significant portion of NO_x emissions. Fiber transportation to pulp and paper mills is also an important contributor. On the converting side, transportation of board to converting mills, purchased electricity, and starch production are the main emitters of smog-related substances.

The CML method identifies much less importance related to NO_x in characterizing the smog indicator. Indeed, its contribution is only 12.4%. Other substances contributing include:

- sulfur dioxide (33.1%, not characterized under smog in TRACI);
- NMVOC (35.6%); and
- others (18.9%).

The relative contribution of the various life cycle stages is similar when using TRACI and CML.

Table 33. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Smog Results by Substances, TRACI Method (Industry-Average)

Life cycle stage/Unit process	NO_x	NMVOC	Others	Total
Total	96.1%	2.7%	1.2%	100%
1. Pulp and papermaking operations	73.1%	2.3%	0.8%	76.1%
Fiber	21.4%	0.2%	0.0%	21.7%
Energy	35.2%	1.1%	0.6%	36.9%
Process emissions and others	16.4%	1.0%	0.1%	17.5%
2. Converting	17.4%	0.2%	0.3%	17.9%
3. Use	4.5%	0.0%	0.0%	4.6%
4. End-of-Life	1.1%	0.2%	0.1%	1.4%

NOTE: In this table, the main individual contributors are displayed in yellow.

6.2.4 Acidification

Table 34 shows that, using the TRACI method, SO_2 and NO_x are the main substances for the acidification indicator, with the pulp and papermaking operations as their main contributor. More specifically:

- emissions of SO_2 from the pulp and papermaking operations life cycle stage arise mainly from purchased power, burned natural gas, and burned coal;
- emissions of NO_x from the pulp and papermaking operations life cycle stage are mainly due to wood combustion and purchased power; and
- natural gas used at converting facilities and production of purchased power used by converting facilities are significant contributors to SO_2 emissions.

The CML method gives more importance to SO_2 (74.9%) compared to NO_x (19.1%) than TRACI. This has little effect on the relative contribution of the life cycle stages.

Table 34. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Acidification Results by Substances, TRACI Method (Industry-Average)

Life cycle stage/Unit process		NO_x	SO_2	Others	Total
Total		27.8%	61.8%	10.3%	100%
1. Pulp and papermaking operations		21.2%	53.3%	7.2%	81.7%
	Fiber	6.2%	1.6%	0.1%	7.9%
	Energy	10.2%	48.2%	2.8%	61.2%
	Process emissions and others	4.8%	3.5%	4.3%	12.5%
2. Converting		5.0%	8.3%	1.1%	14.4%
3. Use		1.3%	0.1%	0.0%	1.5%
4. End-of-Life		0.3%	0.1%	2.0%	2.4%

NOTE: In this table, the main individual contributors are displayed in yellow.

6.2.5 Eutrophication

Table 35 shows that, using the TRACI method, NO_x, total nitrogen released to water, total phosphorus released to water, and a mix of other substances (mostly BOD and COD) contribute the most to eutrophication. Contributors to NO_x were discussed previously for the acidification indicator. Releases of total nitrogen, total phosphorus, and BOD are mostly attributable to pulp and paper mills. Note that the emissions of nitrogen and phosphorus from pulp and paper mills were modeled and are highly uncertain.

Table 35. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Eutrophication Results by Substances, TRACI Method (Industry-Average)

Life cycle stage/Unit process		NO_x	Total N (water)	Total P (water)	Others	Total
Total		16.6%	25.3%	33.9%	24.2%	100%
1. Pulp and papermaking operations		12.6%	25.3%	30.3%	15.5%	83.7%
	Fiber	3.7%	0.0%	0.9%	0.5%	5.1%
	Energy	6.1%	0.0%	1.6%	6.8%	14.5%
	Process emissions	2.5%	25.2%	26.9%	6.2%	60.9%
	Rest	0.3%	0.0%	0.9%	2.0%	3.2%
2. Converting		3.0%	0.0%	2.4%	5.5%	10.8%
3. Use		0.8%	0.0%	0.0%	0.1%	0.9%
4. End-of-Life		0.2%	0.0%	1.3%	3.1%	4.6%

NOTE: In this table, the main individual contributors are displayed in yellow.

CML gives much more importance to nitrogen oxides compared to nitrogen and phosphorus than TRACI for the eutrophication impact category. More specifically, the contributions to the total score of the various substances are as follows:

- NO_x: 50.1%;
- phosphorus to water: 12.6%;
- Phosphorus to soil: 11.0%; and
- others: 26.3%.

6.2.6 Respiratory Effects (Human Health Particulates)

As expected, results presented in Table 36 show that particulates and SO_2 are the main substances of concern related to respiratory effects. Processes contributing to SO_2 have been discussed previously. The energy used at pulp and paper mills, and more specifically the combustion of biofuel and coal, are the main contributors to particulate emissions.

Table 36. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Respiratory Effects Results by Substances, TRACI Method (Industry-Average)

Life cycle stage/Unit process	SO_2	Particulates	Others	Total
Total	46.0%	49.0%	5.0%	100%
1. Pulp and papermaking operations	39.7%	47.8%	3.4%	90.9%
Fiber	1.2%	5.6%	0.8%	7.7%
Energy	35.9%	42.1%	1.9%	79.8%
Rest	2.6%	0.1%	0.7%	3.4%
2. Converting	6.2%	1.1%	1.0%	8.3%
3. Use	0.1%	0.0%	0.2%	0.3%
4. End-of-Life	0.1%	0.1%	0.4%	0.6%

NOTE: In this table, the main individual contributors are displayed in yellow.

6.2.7 Fossil Fuel Usage

Two different indicators were studied concerning fossil fuel usage:

- TRACI's **fossil fuel depletion** (FF) indicator that accounts for the fact that continued extraction and production of fossil fuels tend to consume the most economically recoverable reserves first so that continued extraction will become more energy intensive in the future; and
- GaBi's **non-renewable primary energy** (NRPE) demand that evaluates the total non-renewable energy requirements throughout the life cycle of the studied product.

These two indicators provide different information; hence, were both studied.

Table 37 shows that natural gas and crude oil are the fuels that contribute the most towards the fossil fuel depletion indicator. The following operations consume the most natural gas: pulp and paper mills, converting facilities, and power production for both pulp and paper mills and converting facilities. Crude oil is mainly used for transportation (e.g., fiber to pulp and paper mills, and containerboard to converting facilities) and for forest-/sawmill-related operations.

NOTE: In this table, the main individual contributors are displayed in yellow.

Table 38 shows that, while coal was not an important contributor to fossil fuel depletion, it is an important contributor to non-renewable primary energy demand. Coal burned at pulp and paper mills and from purchased energy is the main contributor to life cycle coal consumption.

Table 37. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Fossil Fuel Depletion Results by Fuels, TRACI Method (Industry-Average)

Life cycle stage/Unit process		Crude oil	Natural gas	Others	Total
Total		16.6%	82.1%	1.3%	100.0%
1. Pulp and papermaking operations		8.2%	65.9%	1.0%	75.1%
	Fiber	5.7%	1.0%	0.0%	6.8%
	Energy	1.7%	63.0%	1.0%	65.7%
	Rest	0.8%	1.9%	0.0%	2.7%
2. Converting		6.1%	16.0%	0.3%	22.4%
	Natural gas used at converting	0.1%	8.8%	0.0%	8.9%
	Transportation of containerboard	2.7%	0.2%	0.0%	2.8%
	Others (mainly purchased power)	3.4%	7.0%	0.3%	10.6%
3. Use		1.9%	0.1%	0.0%	2.1%
4. End-of-Life		0.3%	0.1%	0.0%	0.5%

NOTE: In this table, the main individual contributors are displayed in yellow.

Table 38. Contribution of the Various Life Cycle Stages/Groups of Unit Processes to the Non-Renewable Primary Energy Results by Fuels, GaBi Method (Industry-Average)

Life cycle stage/Unit process		Crude oil	Coal	Natural Gas	Others	Total
Total		14.8%	13.4%	71.0%	0.8%	100.0%
1. Pulp and papermaking operations		7.4%	10.3%	56.9%	0.4%	75.0%
	Fiber	5.1%	0.3%	0.9%	0.1%	6.5%
	Energy	1.5%	10.0%	54.4%	0.2%	66.1%
	Rest	0.7%	0.1%	1.7%	0.0%	2.4%
2. Converting		5.5%	3.1%	13.9%	0.3%	22.7%
	Natural gas used at converting	0.4%	0.1%	7.3%	0.0%	7.8%
	Transportation of containerboard	2.4%	0.0%	0.1%	0.0%	2.5%
	Others (mainly purchased power)	2.7%	3.0%	6.5%	0.3%	12.4%
3. Use		1.7%	0.0%	0.1%	0.0%	1.8%
4. End-of-Life		0.3%	0.0%	0.1%	0.0%	0.4%

NOTE: In this table, the main individual contributors are displayed in yellow.

6.2.8 Renewable Energy Consumption

The GaBi method was used to compute the primary renewable energy demand (RPE). Renewable energy demand is mainly from the pulp and paper making operations life-cycle stage (90%) and consists of hogged fuel (self-generated and purchased) and black liquor solids.

6.2.9 Water Use and Water Consumption

As shown in Figure 19, the pulp and papermaking operations life cycle stage is the main contributor to water use but not to water consumption. Within the pulp and papermaking operations life-cycle stage, it is the pulp and paper mills that use the most water, but they return a significant portion to the environment. Within converting, some chemicals contribute significantly to water use and consumption: starch and ink.

6.3 Sensitivity Analyses

This section presents results of sensitivity analyses that have been performed on parameters that contribute significantly to the results and/or have significant uncertainty associated with them.

- Utilization rate of recycled fiber; and
- Recovery rate.

6.3.1 Utilization Rate of Recycled Fiber (UR)

In this analysis we test the sensitivity of the impact scores to variation in UR (Base case: 56%, Low: 50% and High: 60%). UR cannot be varied independently; hence, this sensitivity analysis was undertaken by varying the relative proportions of 100% board in the the board mix. Figure 21 shows the result for the sensitivity analysis performed with varying UR. It was observed that results are completely consistent for global warming (GW,S), acidification, and water consumption. The impact scores for smog, ozone depletion, eutrophication, respiration, and renewable and non-renewable energy demand showed partially consistent results, with lower UR having a higher impact. Global warming impacts (GW,F) were observed to be most sensitive to UR changes mainly because of the carbon removal associated with fresh fiber that decreases with increase in UR.

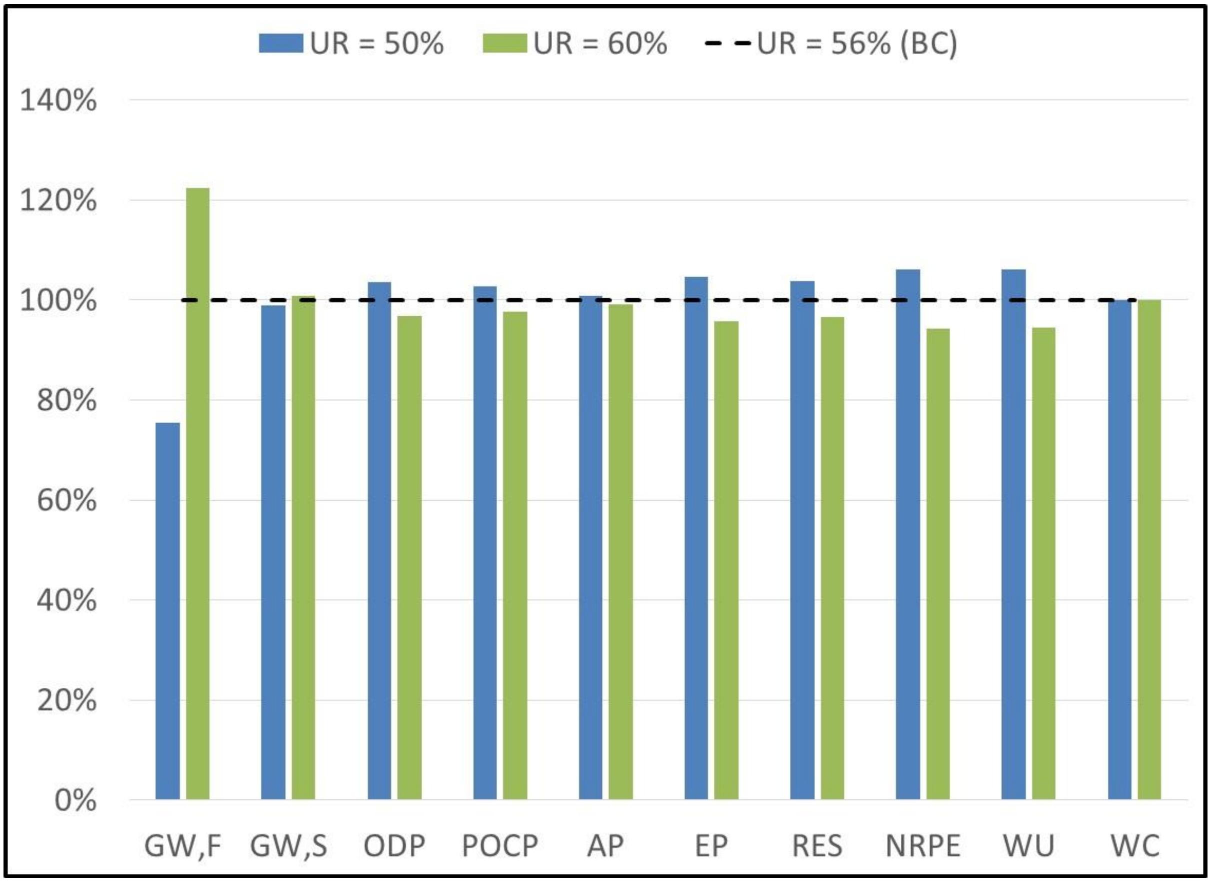


Figure 23. Sensitivity Analysis on Utilization Rate

6.3.2 Recovery Rate (RR)

AF&PA started to report recycling rate as a 3-year average to eliminate potential large swings between annual numbers. In this LCA, we used the 3-year average with 2020 as the midpoint [i.e., average 2019 (91.2%), 2020 (88.8%), and 2021 (91.4%)], which is 90.5%. In this sensitivity analysis, we test 88% and 92%. Figure 22 shows the result for the sensitivity analysis performed with varying RR. It was observed that results are consistent for all categories except for global warming (GW,F). When recovery rate is increased, less GHGs are released at the end-of-life for the same carbon removal, which will show only using GW,F.

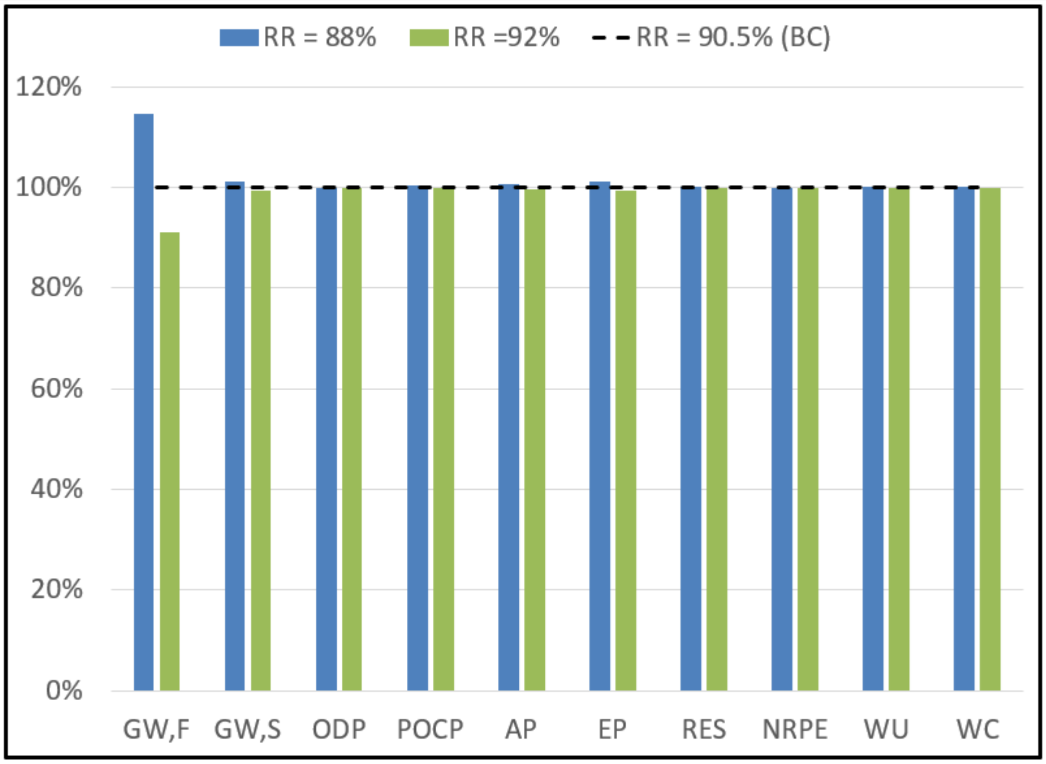


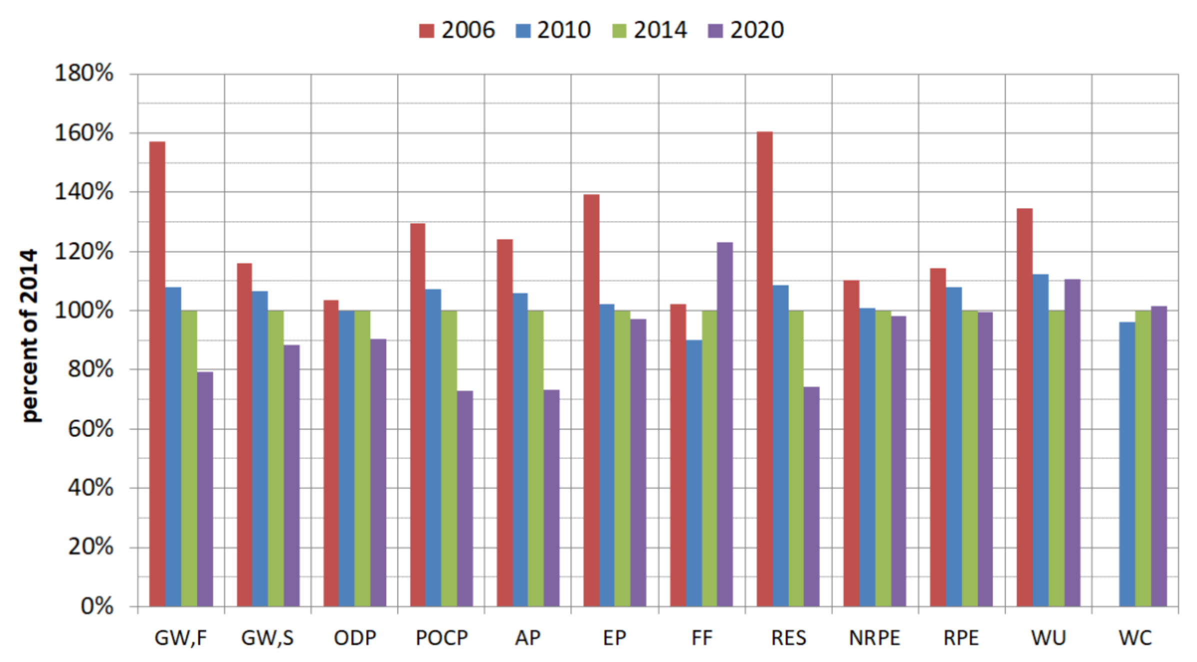
Figure 24. Sensitivity Analysis on Recovery Rate

7. RESULTS AND INTERPRETATION: YEAR-TO-YEAR COMPARISON FOR INDUSTRY-AVERAGE PRODUCT

7.1 Comparison Results

Figure 25 compares the impact/inventory indicators results obtained for 2020 with those obtained for 2006, 2010, and 2014. In general, changes of less than 10% are not considered meaningful (Franklin Associates 2004).

It can be seen from the figure above that most environmental improvement occurred between 2006 and 2020. Between 2014 and 2020, the environmental performance was relatively stable with modest improvement, mainly in renewable primary energy demand (RPE), non-renewable primary energy demand (NRPE), and eutrophication (EP), and with modest increase in water consumption (WC) and water use (WU). Each indicator is further discussed below, focusing on the differences observed between 2014 and 2020.



Indicator		Unit	2006	2010	2014	2020	% change 2020-2014	% change 2020-2010	% change 2020-2006
Global warming, flow accounting	GW,F	kg CO$_2$ eq.	0.82	0.56	0.52	0.41	-20.5%	-26.4%	-49.5%
Global warming, stock accounting	GW,S	kg CO$_2$ eq.	N/Av.	1.53	1.43	1.27	-11.7%	-17.2%	-23.8%
Ozone depletion	ODP	kg CFC11 eq.	7.1E-08	6.9E-08	6.9E-08	6.2E-08	-9.7%	-9.5%	-12.7%
Photo-chemical oxidation	POCP	kg O$_3$ eq.	0.16	0.13	0.12	0.09	-27.0%	-32.0%	-43.6%
Acidification	AP	kg SO$_2$ eq.	0.015	0.013	0.012	0.009	-26.7%	-30.8%	-41.0%
Eutrophication	EP	kg N eq.	1.3E-03	9.8E-04	9.5E-04	9.3E-04	-2.8%	-5.0%	-30.3%
Respiratory inorganics	RES	kg PM2.5 eq.	1.6E-03	1.1E-03	9.7E-04	7.2E-04	-25.7%	36.6%	-53.7%
Fossil fuel depletion	FF	MJ Surplus	1.80	1.59	1.76	2.17	23.2%	-31.5%	20.6%
Non-renewable primary energy demand	NRPE	MJ	20.5	18.72	18.59	18.27	-1.7%	-2.4%	-10.9%
Renewable primary energy demand	RPE	MJ	11.1	10.5	9.73	9.69	-0.4%	-7.7%	-13.0%
Water use	WU	kg	52.8	44.04	39.24	43.37	10.5%	-1.5%	-17.9%
Water consumption	WC	kg	N/Av.	10.02	10.43	10.59	1.5%	-26.4%	N/Av.

Figure 25. Comparison of 2020, 2014, 2010, and 2006 Impact Scores

7.1.1 Global Warming

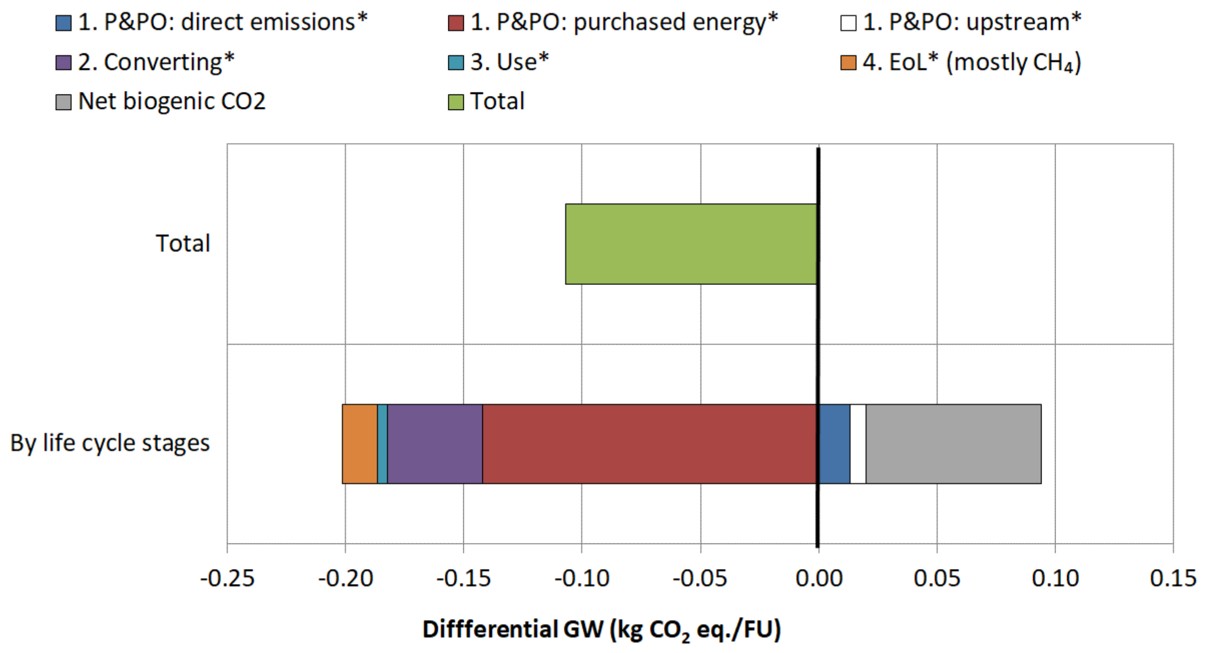
Between 2014 and 2020, the global warming indicator result decreased by 20.5% while using flow accounting (GW,F) and by 11,7% while using stock change accounting (GW,S). Figure 26 provides insight into the different parameters that affected the difference between the two years for flow accounting.

GHG emissions were reduced in some respects:

- There was a significant reduction in GHG emissions associated with purchased energy (both for pulp and paper making and converting) due both to a reduction in purchased energy and in a greening of the grid;
- End-of-life emissions were reduced due to a slight increase in recovery rate.

GHG emissions were increased in some other respects:

- The net emissions of biogenic GHGs increased.
- There was a modest increase in direct GHG emissions at pulp and paper mills, mainly because of more energy generated on-site compared to purchased.



*In this figure, P&PO means pulp and papermaking operations. The pulp and paper making life cycle stage was separated into direct emissions from pulp and paper mills (e.g., fuel combustion at containerboard mill), emissions from pulp and paper mills purchased energy, and other upstream emissions (e.g., from producing the chemicals needed in pulp and papermaking). Emissions from the four life cycle stages exclude biogenic CO$_2$, for which a net value is presented separately.

Figure 26. Explanation of the Difference in GHG Emissions between 2020 and 2014

Figure 27 below illustrates the various types of emissions/removals relevant to the flow accounting method. Note that emissions of both biogenic CO_2 and non-biogenic CO_2 GHGs are decreasing over time.

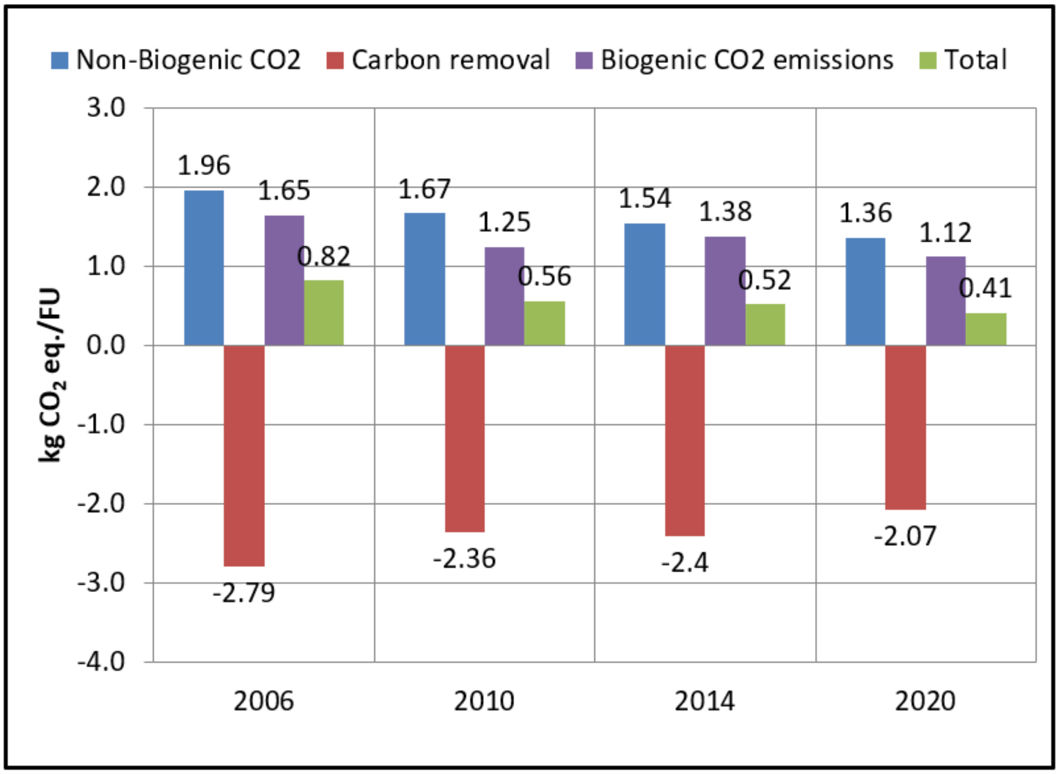


Figure 27. Yearly Comparison of Global Warming Results, Details of the Flow Accounting Method

The indicator for quantifying climate change impacts and the approach for accounting for biogenic CO_2 have the potential to have a significant effect on the comparison of results in different years. For this reason, the flow accounting method used in this study is compared to a stock change accounting method and to quantifying non-biogenic CO_2 GHGs only. The results, presented in Figure 28, show that applying stock change accounting also shows a significant decrease in global warming between 2014 and 2020. This is mainly due to an increase in the share of 100%-recycled product in the containerboard mix, and to a reduction of energy consumption and/or switch to less carbon intensive fuels at containerboard mills.

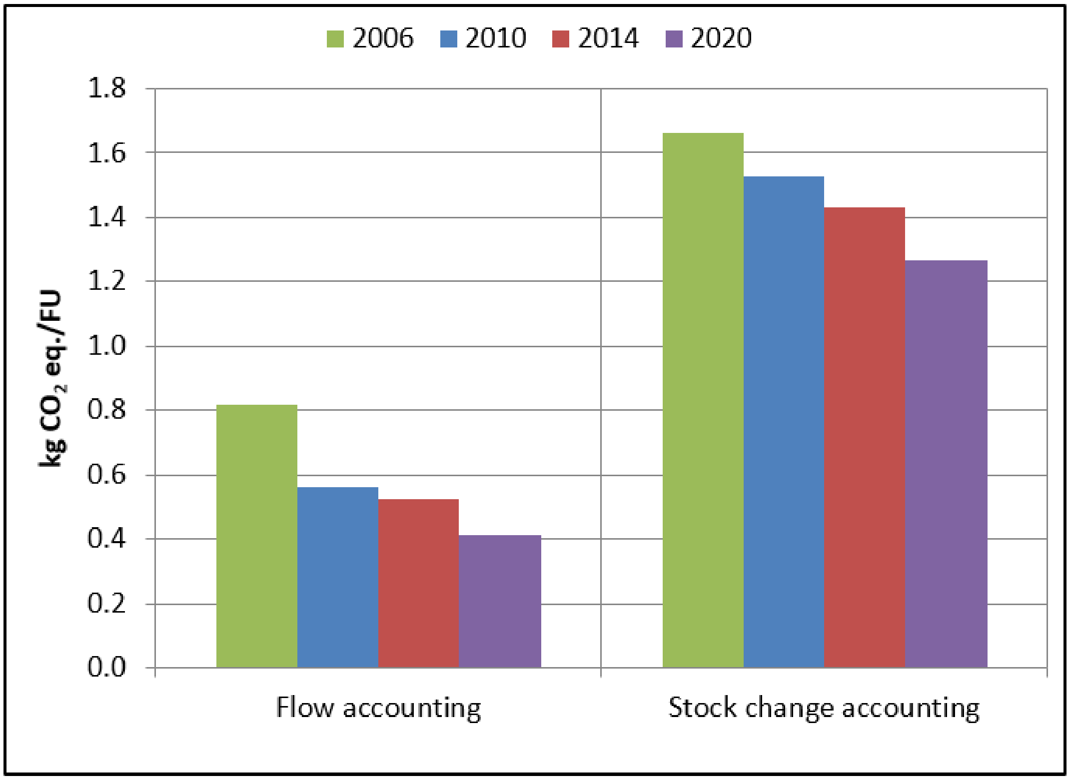


Figure 28. Effect of Biomass CO_2 Accounting on Yearly Comparison

7.1.2 Ozone Depletion

The release of ozone depleting substances remained relatively stable between 2014 and 2020.

7.1.3 Smog

Smog was reduced by 27% between 2014 and 2020. The main factors for this reduction are:

- Greening of the grid; and
- Lower consumption of coal at containerboard mills.

7.1.4 Acidification

Acidification was reduced by 27% between 2014 and 2020. The main factors for this reduction are:

- Greening of the grid; and
- Lower consumption of coal at containerboard mills.

7.1.5 Eutrophication

There was no meaningful change in eutrophication between 2014 and 2020.

7.1.6 Fossil Fuel Depletion, Non-Renewable Primary Energy Demand, and Renewable Energy Demand

Between 2014 and 2020, the impact score for fossil fuel depletion increased by 23%. The main driver for this increase is the increased share of natural gas in the overall fuel mix. That said, there were no meaningful changes in total energy use.

7.1.7 Respiratory Effects

The result of the respiratory effects indicator was reduced by 26% between 2014 and 2020 mainly due to reduction of emissions of SO_2 and particulates from containerboard mills, primarily due to more natural gas in the fuel mix.

7.1.8 Water Use and Consumption

There was a 10.5% increase in water use between 2014 and 2020. The increase in reported water use occurred mainly in the pulp and papermaking operations life cycle stage which is driven mostly by the change in mills participating in the 2014 and 2020 studies. Mills that participated in 2020 but not 2014 had higher water use intensity than average. If all of the mills that participated in 2020 had participated in 2014 and all of the mills that participated in 2014 had participated in 2020 there would have been a 1% decrease in water use at containerboard mills. Water consumption remained relatively stable.

Water consumption remained relatively stable.

7.2 Sensitivity Analyses

In Section 6.3, a sensitivity analysis was performed to evaluate the effect of methodological choices and uncertainty on the calculated environmental performance of the 2020 corrugated product. In this section, the sensitivity of the 2020/2014 yearly comparison was assessed by changing parameters with potential effect on the comparison that are potentially more uncertain than others. More specifically, the effect of the basis weight was tested.

In this study, the annual environmental performance of 1 kg of corrugated product is analyzed and compared. However, two corrugated products of the same weight are not necessarily functionally equivalent given that the functionality of a corrugated product is more related to its volume than to its weight. As such, if the basis weight is lower, less corrugated product, on a mass basis, is required to achieve the same volumetric functionality.

Data in Table 39 show that average corrugated product basis weight has decreased with time. In this sensitivity analysis, we test the effect of the basis weight reduction on the results. For instance, due to the decrease in basis weight, it is possible to argue that only 0.890 kg of corrugated product is needed in 2020 to perform the same function as 0.949 kg of corrugated product in 2014.

The results of this sensitivity analysis are presented in Figure 29 , which shows that making the comparison on a volume-equivalent functional unit would have shown greater reduction, or lower increase, in environmental indicator results. This illustrates that a conservative approach was taken in performing this LCA.

Table 39. Basis Weight Sensitivity Analysis Settings

Year	Basis Weight	Functional Unit Adjustment
2006	138.6 lb/thousand square feet (msf, 0.677 kg/m^2)	1 kg
2010	131.9 lb/thousand square feet (msf, 0.644 kg/m^2)	0.952 kg
2014	131.6 lb/thousand square feet (msf, 0.643 kg/m^2)	0.949 kg
2020	123.4 lb/thousand square feet (msf, 0.602 kg/m^2)	0.890 kg

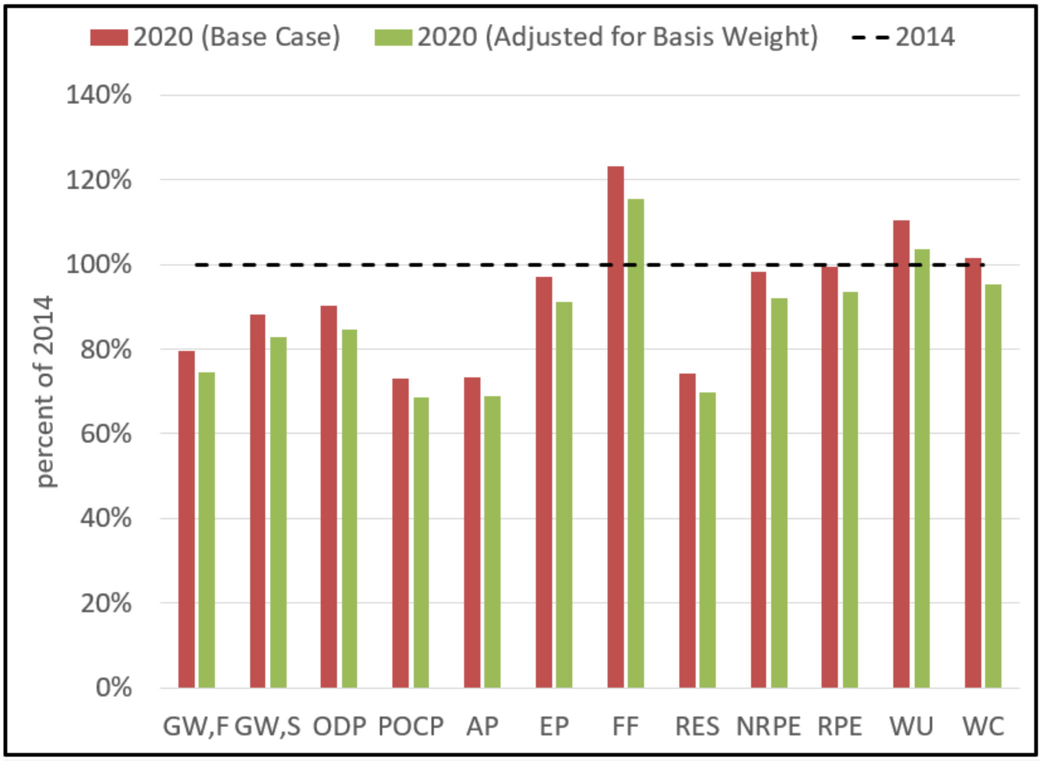


Figure 29. Effect of Functional Unit Definition on Observed Environmental Performance

8. RESULTS AND INTERPRETATION: COMPARISON OF 100%-RECYCLED TO INDUSTRY-AVERAGE

In this section, the environmental performance of the 100%-recycled product relative to that of the industry-average product is evaluated using two different allocation methods for recycling: the Number of Uses (NOU) Method and the Closed-Loop Approximation with Cut-Off Method. Section 8.1 presents the results using the NOU Method, while section 8.2 presents the results using the Closed-Loop Approximation with Cut-Off Method.

These two methods provide different perspectives on how the environmental load of fresh fiber production processes should be distributed between all usages of the fiber (i.e., fresh fiber and recycled). The main difference between the two methods is that the Closed-Loop Approximation with Cut-Off Method assigns the environmental loads and benefits from fresh fiber material production to the products made of fresh fiber only, while the Number of Uses Method shares the loads and benefits between the products made of fresh fiber and those made of recycled fiber. In addition to the Closed-Loop Approximation with Cut-Off Method used for the industry-average LCA, The Number of Uses method was selected for comparing the 100% recycled product to the industry-average product for several reasons. Among them is a recommendation from an international working group addressing LCI issues, as included in a 1996 report by AF&PA (*Life Cycle Inventory Analysis User's Guide - Enhanced Methods and Applications for the Products Industry*), that this method be used in LCA studies of paper because it is the only one that reflects the complex interactions between fresh and recycled fiber. The results obtained applying both methods are presented for consideration.

8.1 Number-of-Uses Method

8.1.1 Indicator Results and Significant Issues

This section presents the results for the impact categories and inventory indicators for the 100%-recycled product as well as simplified contribution analyses. The results presented are for the Number of Uses (NOU) Method. Note that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

LCIA indicator results are presented in Table 40 and inventory indicators in Table 41.

Table 40. LCIA Indicator Results per Functional Unit (100%-Recycled, NOU Method)

Impact categories proposed by ISO 14047	Nomenclature	TRACI method	CML method	IPCC AR6 GWPs
Global warming, flow accounting	GW,F			1.31 kg CO_2 eq.
Global warming, stock change accounting	GW,S			1.44 kg CO_2 eq.
Global warming, excluding biogenic CO_2	GW,ExclBioCO_2			1.54 kg CO_2 eq.
Stratospheric ozone depletion	ODP	5.99E-08 kg CFC-11 eq.		
Photo-oxidant formation	POCP	0.075 kg O_3 eq.	0.0126 kg C_2H_4 eq.	
Acidification	AP	0.088 kg SO_2 eq.*	0.0132 kg SO_2 eq.	
Nitrification/ Eutrophication	EP	6.33E-4 kg N eq.*	8.48E-4 kg PO_4 eq.	
Depletion of abiotic resources (e.g., fossil fuels, minerals)	FF	2.48 MJ surplus		
Respiratory effects inorganics substances**	RES	4.99E-4 kg PM2.5 eq.		

**Total of air and water.*

Table 41. LCI Indicator Results per Functional Unit (100%-Recycled, NOU Method)

Additional indicator	Nomenclature	Results
Non-renewable primary energy demand	NRPE	20.7 MJ
Renewable primary energy demand	RPE	2.77 MJ
Water use	WU	31.1 kg
Water consumption	WC	14.8 kg

Contribution analyses are presented in Figure 30, Figure 31 and Figure 32. Using the NOU Method, the 100%-recycled product has a similar environmental profile to that of the industry-average product presented previously (Section 6). Notable exceptions include:

- The pulp and papermaking life cycle stage contributes more towards the global warming indicator calculated using flow accounting (GW,F). The reason is that there is very little carbon removal to offset emissions of GHGs.
- The contribution of the pulp and papermaking life cycle stage to water use (WU) is comparatively less significant. However, in the case of the NOU Method, there is an imported fresh fiber production load (NOU credit) that comes with the recovered fiber used in containerboard production. This additional environmental load contributes significantly towards water use.

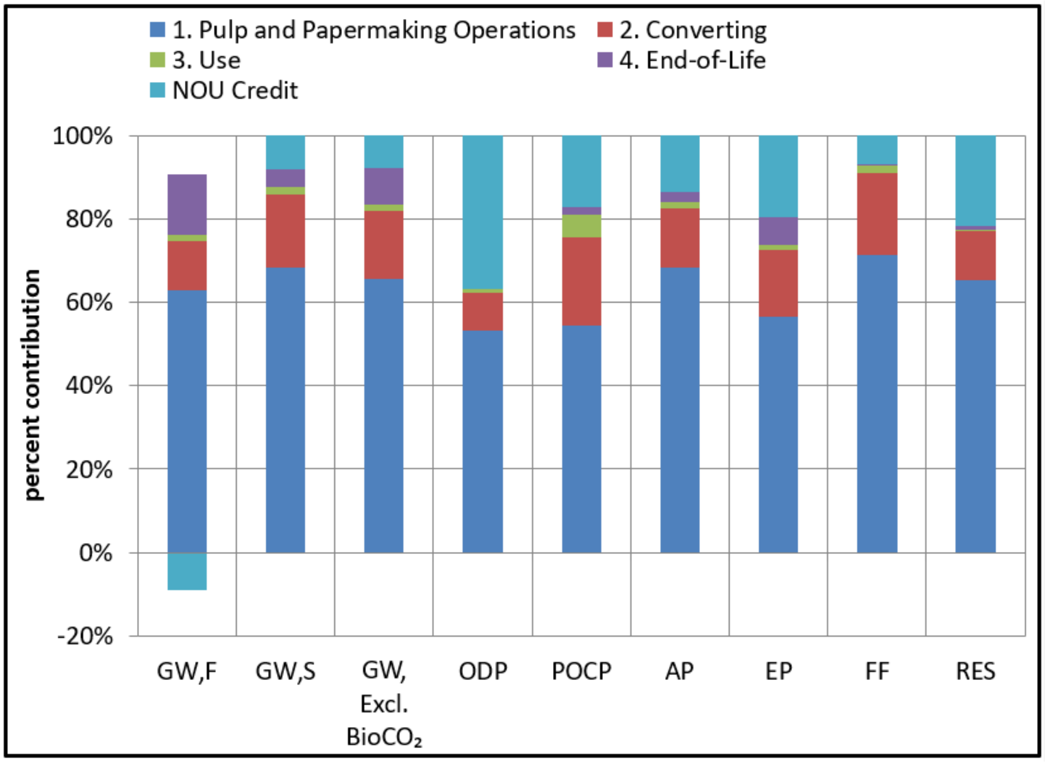


Figure 30. Contribution Analyses for LCIA Indicators, TRACI and IPCC (100%-Recycled, NOU Method)

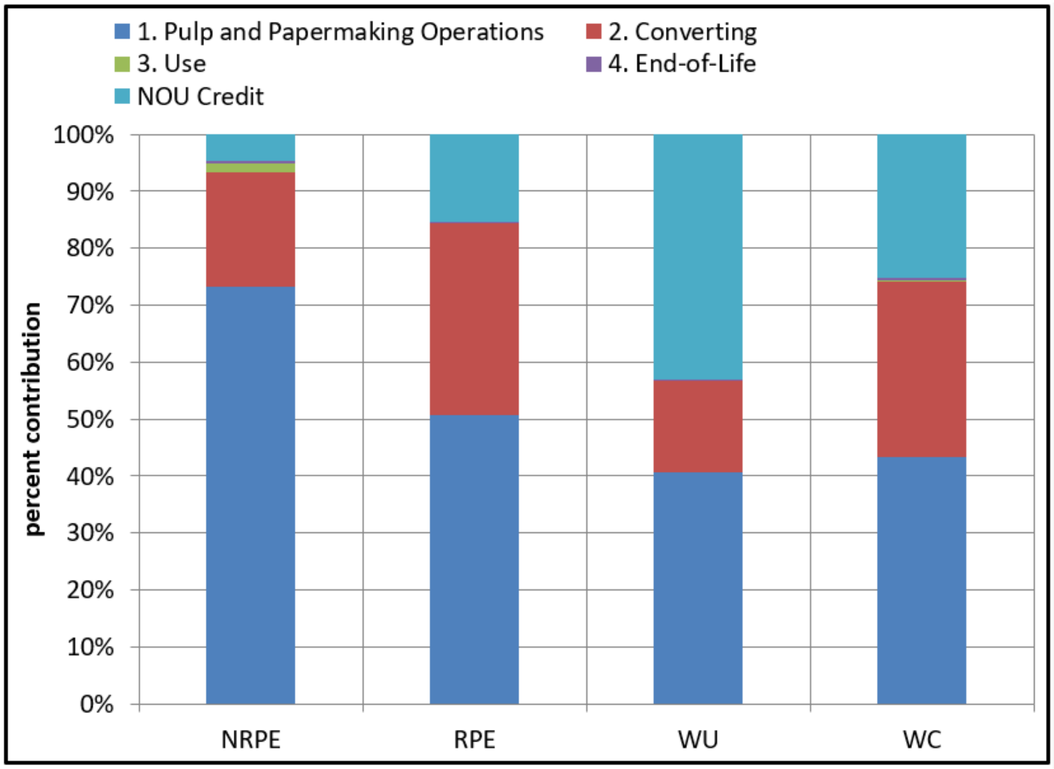


Figure 31. Contribution Analyses for LCI Indicators (100%-Recycled, NOU Method)

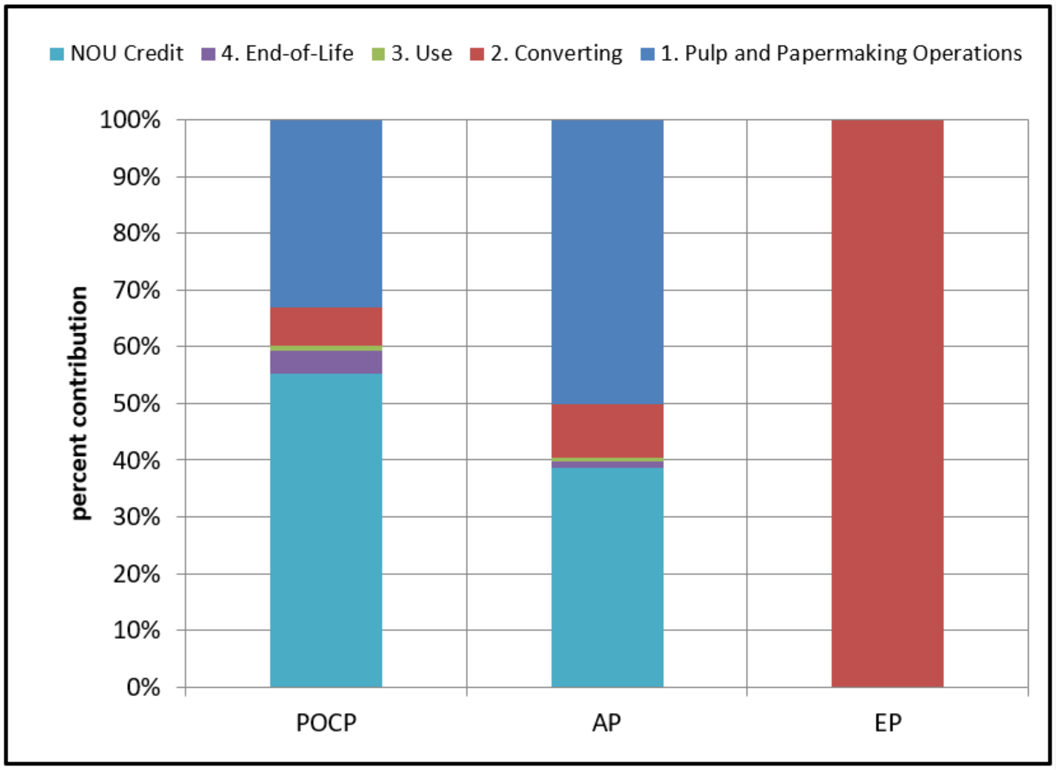


Figure 32. Contribution Analyses for LCIA Indicators, CML Method (100%-Recycled, NOU Method)

8.1.2 Comparison with Industry-Average

Figure 33 compares the LCIA and inventory indicator results for the 100%-recycled and industry-average corrugated product using the NOU Method. It can be seen from the figure that when applying the NOU Method, the 100%-recycled product shows:

- Lower environmental score result than the industry-average product for the following environmental indicators: renewable energy demand (RPE) and water use (WU);
- No meaningful difference compared to the industry-average product for the following environmental indicator: eutrophication (EP); and
- Higher environmental score results for all remaining indicators.

Further details on each indicator are provided next.

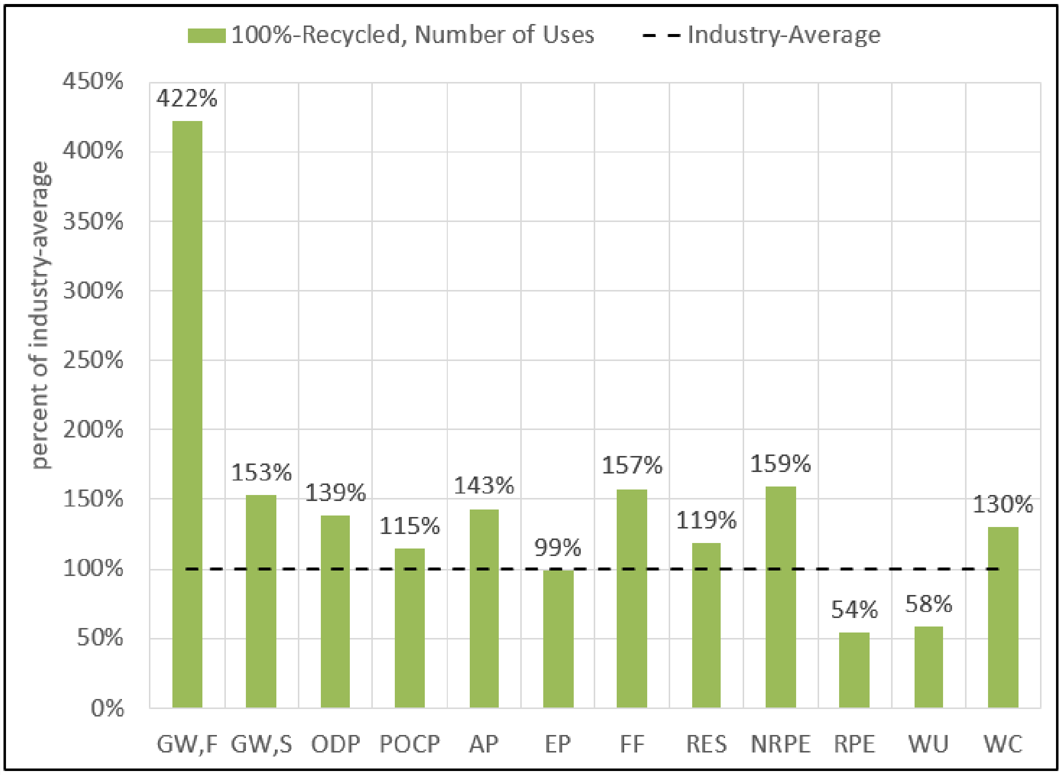


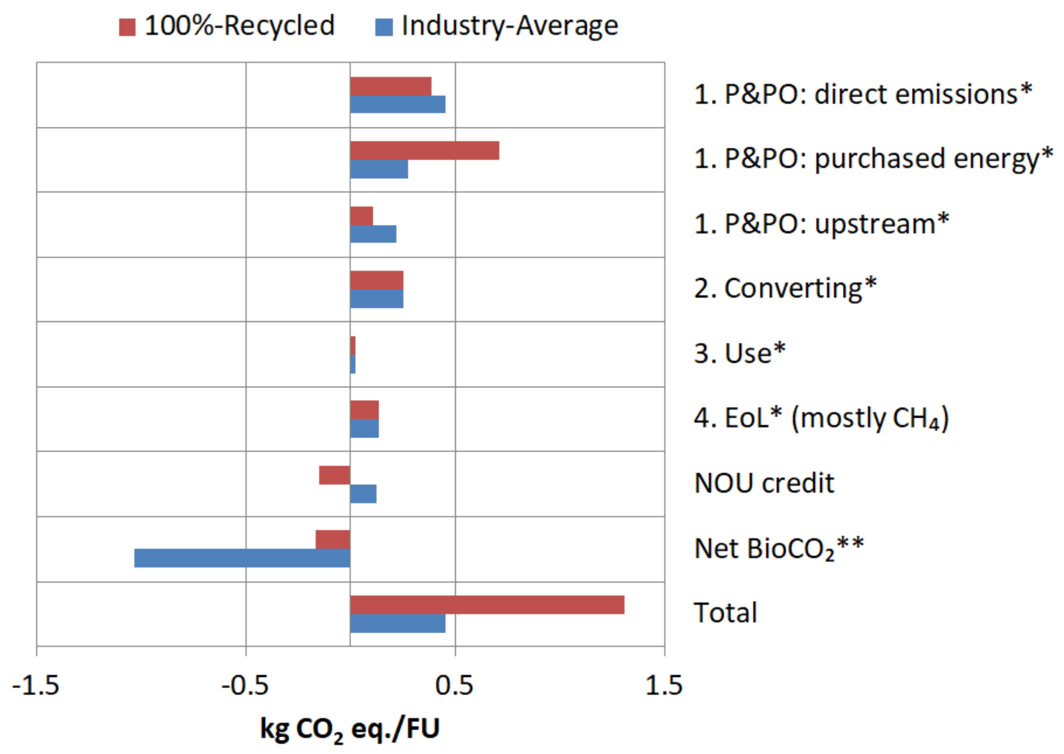
Figure 33. Impact Scores for the 100%-Recycled Product Relative to that of the Industry-Average Product (NOU Method)

8.1.2.1 Global Warming

Using the NOU Method, the global warming results are significantly higher for the 100%-recycled product than for the industry-average product, and this irrespective of the global warming indicator used. Figure 34 explores the drivers for this result when the global warming indicator is calculated using the flow accounting approach (GW,F).

Two main reasons explain this difference:

1) Although the application of the NOU Method involves the import of net carbon sequestration (identified as NOU credit on the figure) benefits from other product systems, there are still significantly more removals of CO_2 from the atmosphere associated with the industry-average that are not offset by emissions at the end-of-life because 89.5% the product is recovered for recycling; and
2) The 100%-recycled product consumes more purchased energy that is almost fully generated using fossil fuels.



*In this figure, P&PO means pulp and papermaking operations. The pulp and paper making life cycle stage was separated into direct emissions from pulp and paper mills (e.g., fuel combustion at containerboard mill), emissions from pulp and paper mills purchased energy, and other upstream emissions (e.g., from producing the chemicals needed in pulp and papermaking). Emissions from the four life cycle stages exclude biogenic CO_2, for which a net value is presented separately. **The net value for biogenic CO_2 does not include any transfer from applying the number of use method.

Figure 34. Difference in GHG Emissions between the Industry-Average and 100%-Recycled Products (NOU Method)

When analyzing the differences in global warming results between the industry-average and 100%-recycled product, it is important to understand the difference between "recovery rate" and "utilization rate." On one hand, the recovery rate is the fraction of old corrugated containers recovered at the end-of-life to be recycled. The recovery rate applies equally to all corrugated products (industry-average or 100%-recycled) because all corrugated products are recovered at the same rate, regardless of their content of recovered fiber. On the other hand, the utilization rate describes the quantity of recovered fiber used in containerboard production. The utilization rate is thus different for 100%-recycled corrugated products compared to that for industry-average products. Methane from landfills is avoided when material is diverted from the waste stream (the amount of which varies based on the recovery rate). Once it is recovered, fiber may go to a number of different uses, including use as raw material for containerboard (affecting the utilization rate). The utilization rate affects emissions primarily via its effects on manufacturing operations and upstream emissions related to production of raw materials and energy.

This report previously examined the differences in industry-average corrugated product between 2014 and 2020 and found that for end-of-life, with respect to greenhouse gas emissions, they were lower in 2020 due to the increased recovery rate (less landfill methane). In the context of comparing 100%-recycled product with industry-average product, methane reduction from landfills is not a factor because the recovery rate, and hence the quantity of product going to landfill, is the same for both product types.

8.1.2.2 Ozone Depletion (ODP)

The releases of ozone-depleting substances are higher for the 100%-recycled than for the industry-average products when applying the NOU Method. There are higher releases of ozone-depleting substances from fresh fiber production processes than for recycling processes. However, when applying the NOU Method, a portion of the releases from fresh fiber production processes are shared over the multiple uses of the fiber, resulting in the first (fresh fiber) use carrying less of the load. The amounts shared are assigned to subsequent (recycled) uses, causing the releases of ozone-depleting substances to be higher for the 100%-recycled product than for the industry-average product.

8.1.2.3 Smog (POCP)

The releases of substances contributing towards the smog indicator are higher for the 100%-recycled product than for the industry-average product when the NOU Method is applied. This can be explained as follows. There are higher releases of substances contributing to the smog indicator from fresh fiber production processes than for recycling processes. However, when applying the NOU Method, a portion of the releases from fresh fiber production processes are shared over the multiple uses of the fiber resulting in the first (fresh fiber) use carrying less of the load. The amounts shared are assigned to subsequent (recycled) uses, causing the releases of substances contributing towards the smog indicator to be higher for the 100%-recycled product than for the industry-average product.

8.1.2.4 Acidification (AP)

The releases of acidifying substances are higher for the 100%-recycled product than for the industry-average product when the NOU Method is applied. This can be explained as follows. There are higher releases of acidifying substances from fresh fiber production processes than for recycling processes. However, when applying the NOU Method, a portion of the releases from fresh fiber production processes is shared over the multiple uses of the fiber resulting in the first (fresh fiber) use carrying less of the load. The amounts shared are assigned to subsequent (recycled) uses, causing the releases of acidifying substance to be higher for the 100%-recycled product than for the industry-average product.

8.1.2.5 Eutrophication (EP)

The releases of eutrophying substances indicator are not significantly different for the 100%-recycled and industry-average products when the NOU Method is applied. This can be explained as follows. There are more releases of eutrophying substances from fresh fiber production processes than for recycling processes. However, when applying the NOU Method, a portion of the releases from fresh fiber production processes are shared over the multiple uses of the fiber resulting in the first (fresh fiber) use carrying less of the load. The amounts shared are assigned to subsequent (recycled) uses, causing the releases of eutrophying substances to become equivalent for the two products.

8.1.2.6 Fossil Fuel Depletion (FF), Non-Renewable Primary Energy Demand (NRPE), and Renewable Energy Demand (RPE)

Using the NOU Method, the 100%-recycled product life cycle results in greater fossil fuel depletion and non-renewable energy demand scores. This can be explained as follows. In this case, recycled and fresh fiber production processes contribute similarly to these two indicators. However, when applying the NOU Method, a portion of fossil fuel usage from fresh fiber production processes is shared over the multiple uses of the fiber resulting in the first (fresh fiber) use carrying less of the load. The amounts shared are assigned to subsequent (recycled) uses, causing the score for the fossil fuel depletion and non-renewable energy demand indicators to be higher for the 100%-recycled product.

Using the NOU Method, the 100%-recycled product consumes less renewable energy than the industry-average. Fresh fiber production processes consume more renewable energy than recycling processes. Although in applying the NOU Method a portion of renewable energy from fresh fiber production processes is shared over the multiple uses of the fiber resulting in the first (fresh fiber) use carrying less of the load and the recycled products more, this is not sufficient to change the overall picture in terms of renewable energy consumption.

8.1.2.7 Respiratory Effects (RES)

The results for the respiratory effects indicator are higher for the 100%-recycled than for the industry-average products when the NOU Method is applied. Although direct particulate releases are lower for the 100%-recycled product, the portion of the fresh fiber production load that is transferred to 100%-recycled products when applying the NOU Method causes these releases to become higher for the 100%-recycled product than for the industry-average product.

8.1.2.8 Water Use (WU) and Water Consumption (WC)

Water use is significantly lower for the 100%-recycled product than for the industry-average product when the NOU Method is applied. This is mainly because pulp and papermaking using recycled fiber requires less water use than when using fresh fiber. However, water consumption is higher for the 100%-recycled than for the industry-average products. Water consumption does go up as a percentage of the intake as water use goes down. Water consumption will also increase on a volumetric basis as water use goes down because temperature management issues become more important, leading to water consumption being equivalent for the two products. However, using the NOU Method, a portion of the fresh fiber production burden is transferred to the recycled products and thus the observed water consumption indicator is higher for the 100%-recycled corrugated product.

8.1.3 Sensitivity Analysis

This section presents results of sensitivity analyses that have been performed on: (a) parameters that contribute significantly to the results and have significant uncertainty associated with them, and (b) methodological choices with potential effects on the results in the context of applying the NOU Method. Sensitivity analyses were performed on the following aspects:

- LCIA method;
- accounting approach for biogenic CO_2;
- board mix; and
- electricity mix for 100%-recycled linerboard and medium.

Results of these sensitivity analyses are discussed in the following paragraphs.

8.1.3.1 LCIA Method

Figure 35 compares the results obtained using the TRACI and CML methods for the acidification (AP), eutrophication (EP), and smog (POCP) indicators. This figure shows that the choice of the method has little effect on the results of the comparison for the acidification and smog indicators. TRACI and CML apply very different weightings to various substances in the eutrophication impact category. These differences are significant enough to affect the results of a comparison between the 100%-recycled and industry-average products. As shown in Figure 35, when using the TRACI indicator, the release of eutrophication substances was 2% lower for the 100%-recycled product than that for the industry-average product. When using the CML method they are 13% higher mainly because CML does not attribute significant importance to phosphorus releases.

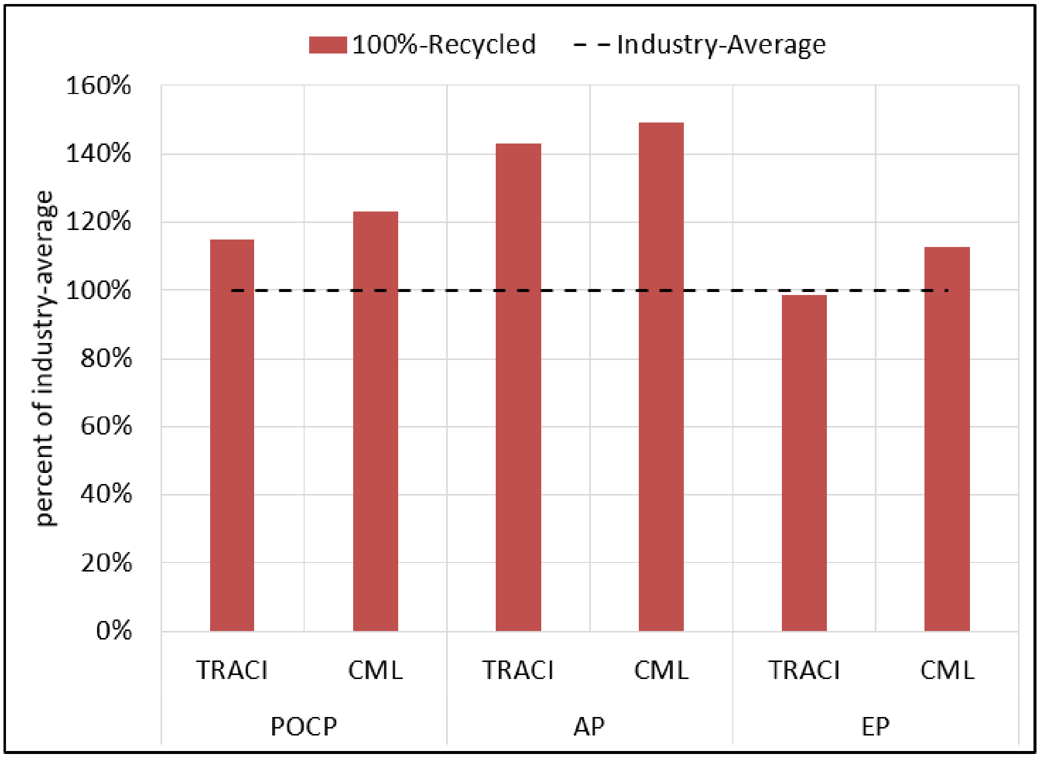


Figure 35. Results for the 100%-Recycled Product Relative to that of the Industry-Average Product: TRACI vs. CML (NOU Method)

8.1.3.2 Accounting Approach for Biogenic CO_2

The effect of the accounting approach used for biogenic CO_2 on the global warming indicator results when the NOU Method is applied was presented in Figure 33 and Table 40. When using flow accounting, the 100%-recycled product has a score for the global warming indicator that is 422% that of the industry-average, whereas the score is approximately 155% of the industry-average score when using stock change accounting or when ignoring biogenic CO_2. This shows that although the magnitude of the difference between 100%-recycled and industry-average products varies significantly depending on the method used, the industry-average product always results in lower global warming impact.

8.1.3.3 Proportion of Each Individual Board Type in the Production Mix

When comparing the 100%-recycled product to the industry-average product, the ratio of linerboard to medium was kept constant, representing a realistic approach because the same product mix is compared. Another approach could have been to compare the actual industry-average corrugated product produced and used in the U.S. to the actual 100%-recycled corrugated product produced and used in the U.S (based on data from AF&PA). As shown in Table 42, applying this alternative approach affects the ratio of linerboard and medium in the corrugated product. While the industry-average product produced and used in the U.S. is made of 65.9% linerboard and 34.1% corrugated medium, the 100%-recycled product produced and used in the U.S. is made of 49.8% linerboard and 50.2% corrugated medium, indicating a difference in exports outside the U.S. of the different containerboard components.

Table 42. Mix of Boards in Corrugated Products

Board type	Industry-Average	100%-Recycled	
	Base Case Scenarios	Base Case Scenario	Actual U.S. Production and Usage
100%-recycled linerboard	15.8%	65.9%	49.8%
All other linerboard	50.1%	0%	0%
Total linerboard	***65.9%***	***65.9%***	***49.8%***
100%-recycled corrugating medium	16.0%	34.1%	50.2%
All other corrugating medium	18.1%	0%	0%
Total corrugating medium	***34.1%***	***34.1%***	***50.2%***

Figure 36 shows that the board mix does not significantly affect the results for most of the indicators except for global warming (GW,F), ozone depletion, and water use when the NOU Method is applied. This is because 100%-recycled linerboard and 100%-recycled medium have very similar environmental performance. The difference in water use is likely due to the data collection issue identified previously. From converting to end-of-life, they are assumed to have the same environmental profile. The production of 100%-recycled linerboard and 100%-recycled medium use similar quantities of fiber and of energy. Other aspects that differ between the two products, such as chemical and additive usage, are not very significant in terms of the overall environmental performance of the two products. With few exceptions, recycled linerboard and recycled medium are produced at the same facilities. The most straightforward method for a mill to allocate environmental load to the two products would be to use mass allocation, which would result in the same environmental profile for the two products on a mass basis.

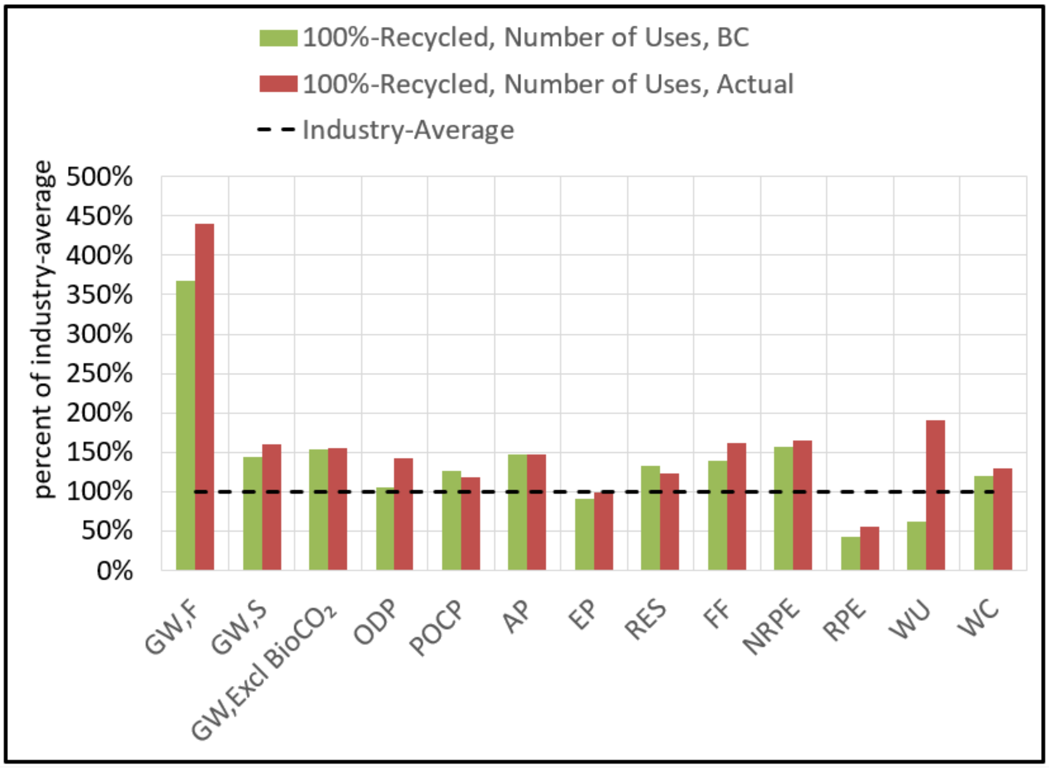


Figure 36. Effect of Board Mix on the Comparison of 100%-Recycled and Industry-Average Products (NOU Method)

8.1.3.4 Electricity Mix for 100%-Recycled Linerboard and Medium

More than 99% of the data collected for 100%-recycled linerboard and 100%-recycled medium were from eastern U.S. states, whereas the sector itself is spread across the nation. One effect of this is to skew the impact of the electricity mix modeled in the study. This sensitivity analysis assesses the effect of the following electricity mix for recycled product (based on 2020 data from Fisher International):

- Recycled linerboard:
    - East: 80.8%
    - West: 15.7%
    - Texas: 3.5%
- Recycled medium:
    - East: 75.1%
    - West: 23.9%
    - Texas: 1.0%

As illustrated in Figure 37, the resulting difference in electricity mix has little effect on the results except for global warming (GW,F) and ozone depletion when the NOU Method is applied.

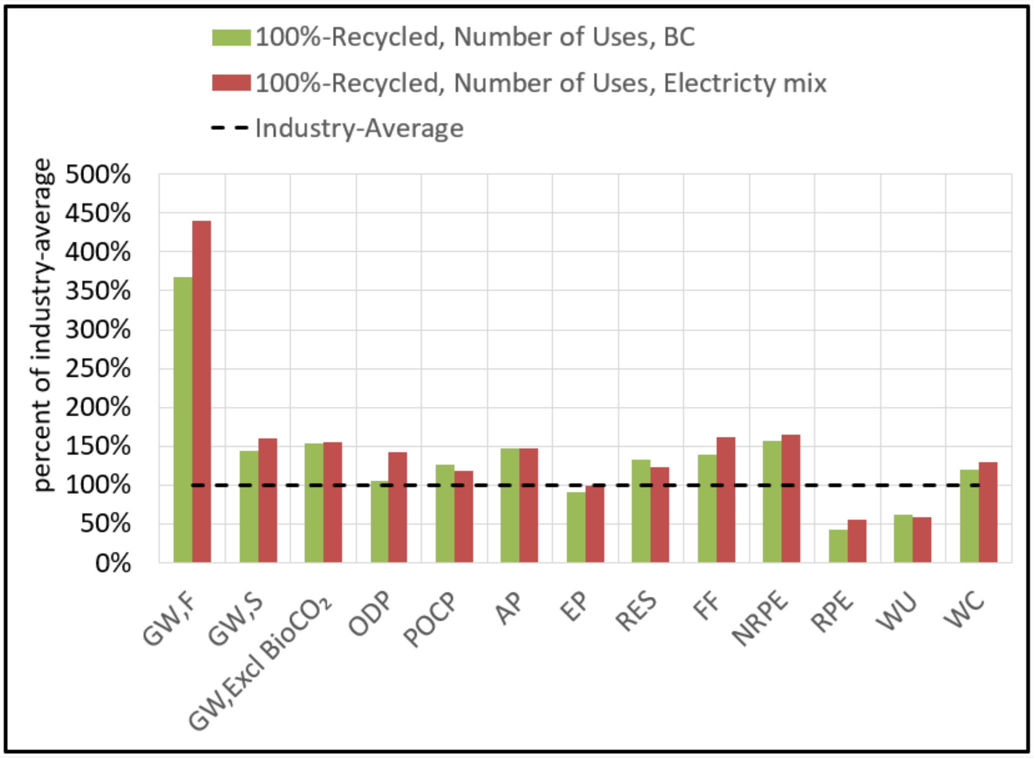


Figure 37. Effect of Electricity Mix on the Comparison of 100%-Recycled and Industry-Average Products (NOU Method)

8.2 Closed-Loop Approximation with Cut-Off Method

8.2.1 Indicator Results and Significant Issues

This section presents the results for the impact categories and inventory indicators for the 100%-recycled product as well as simplified contribution analyses. The results presented are for the Closed-Loop Approximation with Cut-Off Method (hereinafter referred to as the "Cut-Off Method"). Note that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

LCIA indicator results are presented in Table 43 and inventory indicators in Table 44.

Table 43. LCIA Indicator Results per Functional Unit (100%-Recycled, Cut-Off Method)

Impact categories proposed by ISO 14047	Nomenclature	TRACI method	CML method	IPCC AR6 GWPs
Global warming, flow accounting	GW,F			1.45 kg CO_2 eq.
Global warming, stock change accounting	GW,S			1.32 kg CO_2 eq.
Global warming, excluding biogenic CO_2	GW,ExclBioCO_2			1.42 kg CO_2 eq.
Stratospheric ozone depletion	ODP	3.79E-08 kg CFC-11 eq.		
Photo-oxidant formation	POCP	0.0625 kg O_3 eq.	1.17E-3 kg C_2H_4 eq.	
Acidification	AP	0.0076 kg SO_2 eq.*	0.0124 kg SO_2 eq.	
Nitrification/ Eutrophication	EP	5.09E-4 kg N eq.*	7.56E-4 kg PO_4 eq.	
Depletion of abiotic resources (e.g., fossil fuels, minerals)	FF	2.31 MJ surplus		
Respiratory effects inorganics substances**	RES	3.92E-4 kg PM2.5 eq.		

**Total of air and water.*

Table 44. LCI Indicator Results per Functional Unit (100%-Recycled, Cut-Off Method)

Additional indicator	Nomenclature	Results
Non-renewable primary energy demand	NRPE	19.7 MJ
Renewable primary energy demand	RPE	2.34 MJ
Water use	WU	17.7 kg
Water consumption	WC	11.1 kg

Contribution analyses are presented in Figure 38, Figure 39 and Figure 40. The 100%-recycled product has a similar environmental profile as that of the industry-average product except for the pulp and papermaking operation life cycle stage. When compared to the industry-average product, the pulp and papermaking life cycle stage is characterized mainly by:

- no fresh fiber feedstock and hence, no associated carbon removals;
- higher consumption of recovered fiber; and
- a very different energy profile (e.g., almost no renewable energy, more purchased steam, etc.).

As a result, the contribution analyses show quite different results for some indicators. For instance, while the pulp and papermaking operations (P&PO) life cycle stage was an insignificant contributor to the global warming indicator (GW,F) for the industry-average product, it is the main contributor for the 100%-recycled product. Also, the P&PO stage contributes less to the renewable energy, water use, and water consumption indicators than it does for the industry-average product.

In the case of the 100%-recycled product, the P&PO stage is the main contributor to all indicators. The converting life cycle stage is a significant contributor to all indicators. End-of-life is only relevant for the global warming indicator. The choice of the LCIA method did not greatly affect the results.

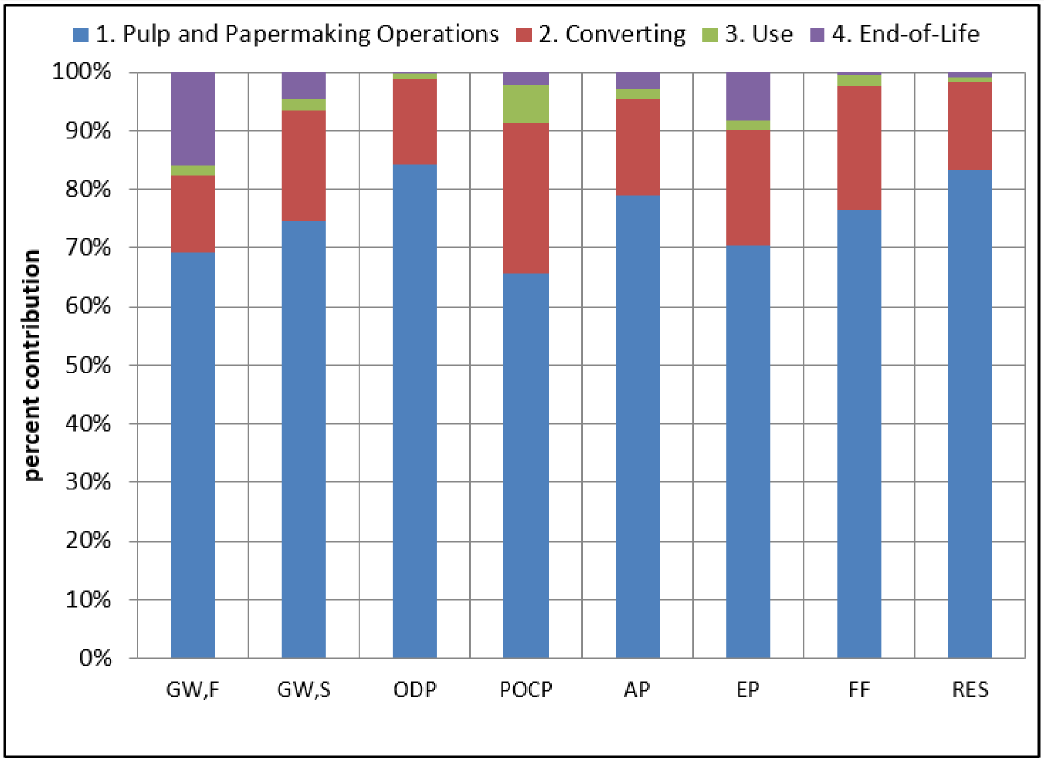


Figure 38. Contribution Analyses for LCIA Indicators, TRACI and IPCC (100%-Recycled, Cut-Off Method)

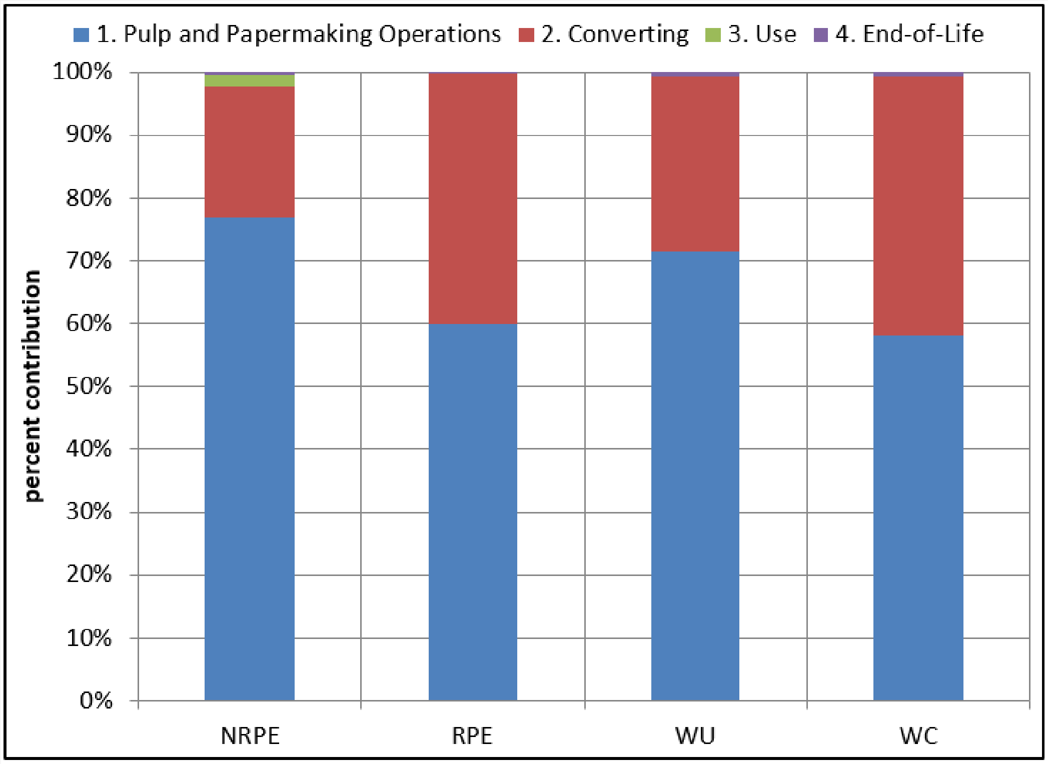


Figure 39. Contribution Analyses for LCI Indicators (100%-Recycled, Cut-Off Method)

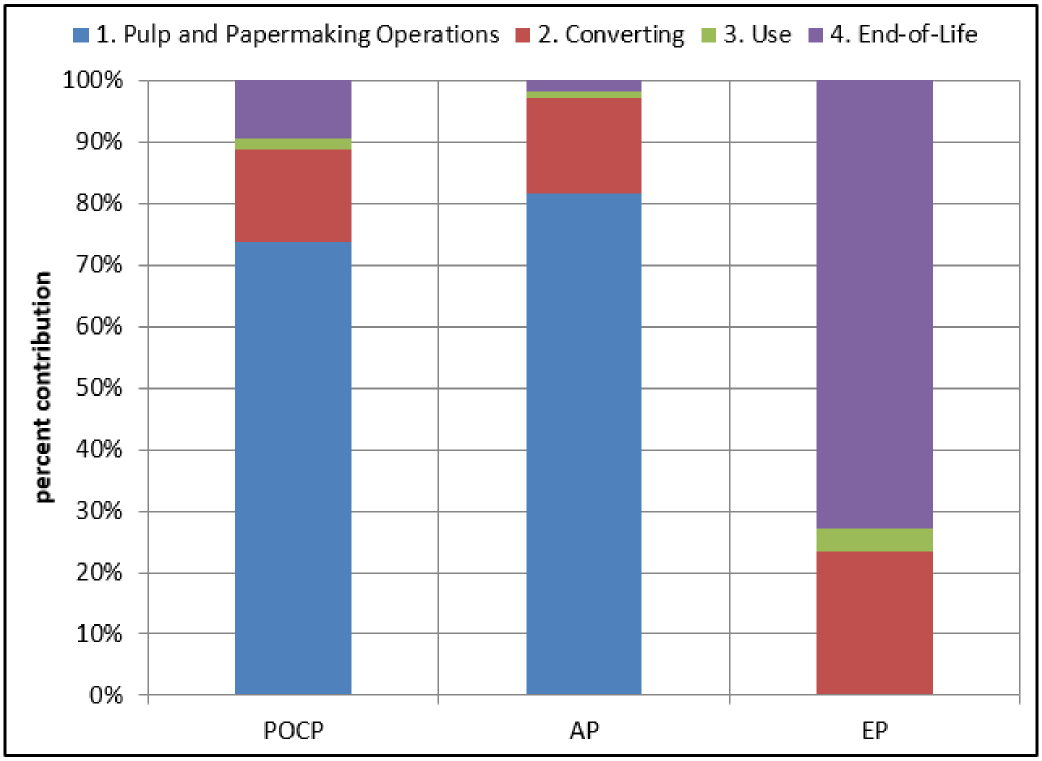


Figure 40. Contribution Analyses for LCIA Indicators, CML Method (100%-Recycled, Cut-Off Method)

Table 45 presents the cradle-to-gate carbon footprint results for 1 kg of containerboard and 1 kg of corrugated product.

Table 45. Cradle-to-Gate Carbon Footprint for the 100% Recycled Product

Product	Flow accounting				Stock change accounting	Excluding biogenic CO_2[a, b]
	Non-biogenic CO_2 GHGs[a]	Biogenic CO_2	Biogenic removal	Net		
	kg CO_2 eq./kg					
100% Recycled[c] containerboard	0.93	0.075	-0.084	0.92	0.90	0.92
100%-Recycled[c] corrugated product	1.27	0.084	0.16	1.20	1.24	1.26

[a] Refers to fossil GHGs and other non-CO_2 biogenic GHGs. Value typically needed for "purchased goods and services" in GHG reporting and needed for third-party Environmental Product Declarations (EPDs). [c] Cut-off method. NOTE: For flow accounting, the GWP of CH_4 is 29.8 kg CO_2 eq./kg. For stock change accounting and accounting that excludes biogenic CO_2, the GWP of CH_4 is 27 kg CO_2 eq./kg.

8.2.2 Comparison of Contributions for NOU and Cut-Off Method

Figure 41 compares the contribution of the life cycle stages to the various LCIA indicators. In this figure, the burden imported with the usage of recycled fiber (which would be included in the pulp and papermaking operations life cycle stage) is shown separately in black. It can be observed that importing some environmental load from fresh fiber production would significantly increase the contribution of this life cycle stage with the exception of GW,F where a net removal would be imported.

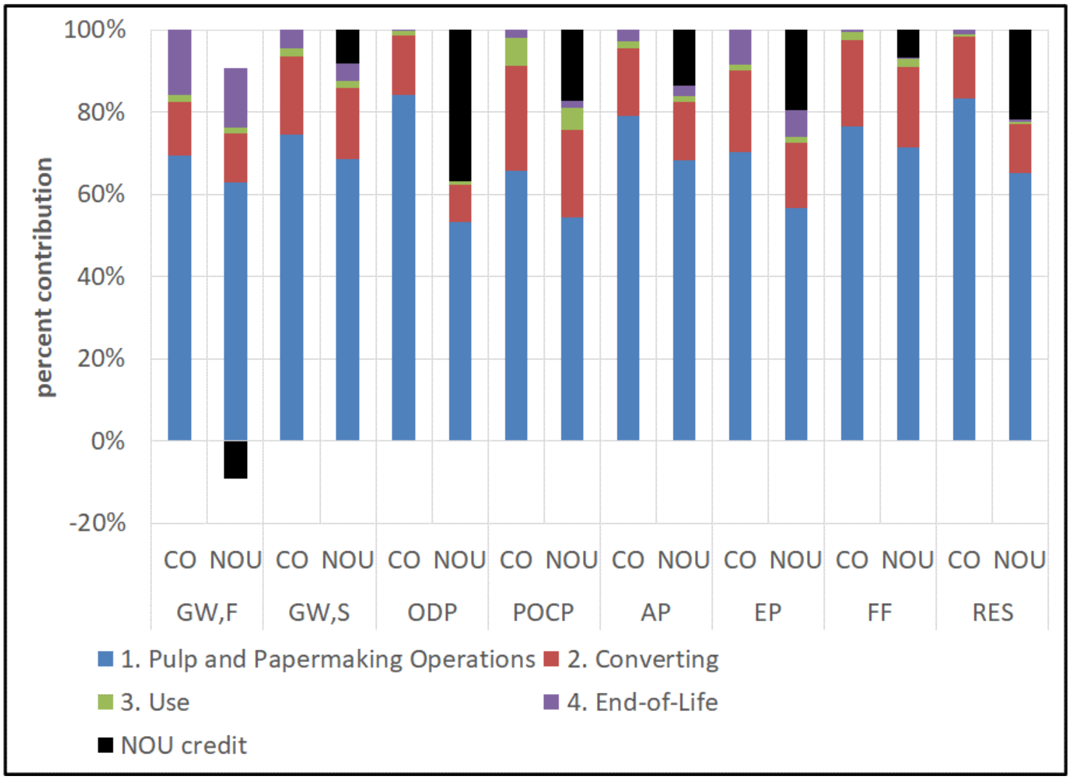


Figure 41. Comparison of the Cut-Off (CO) and NOU method with regards to life cycle contributions

8.2.3 Comparison with Industry-Average

Figure 42 compares the LCIA and inventory indicator results for the 100%-recycled and industry-average corrugated products using the Cut-Off Method. It can be seen from the figure that, when applying the Cut-Off Method, the 100%-recycled product shows:

- Lower environmental score results than the industry-average product for the following environmental indicators: ozone depletion (ODP), smog, (POCP), acidification (AP), eutrophication (EP), respiratory inorganics (RES), renewable energy demand (RPE), and water use (WU);
- No significant difference with the industry-average product for the following environmental indicators: fossil fuels depletion (FF), non-renewable energy demand (NRPE), and water consumption (WC); and
- Higher environmental score results for the global warming indicator.

Further details on each indicator are provided next.

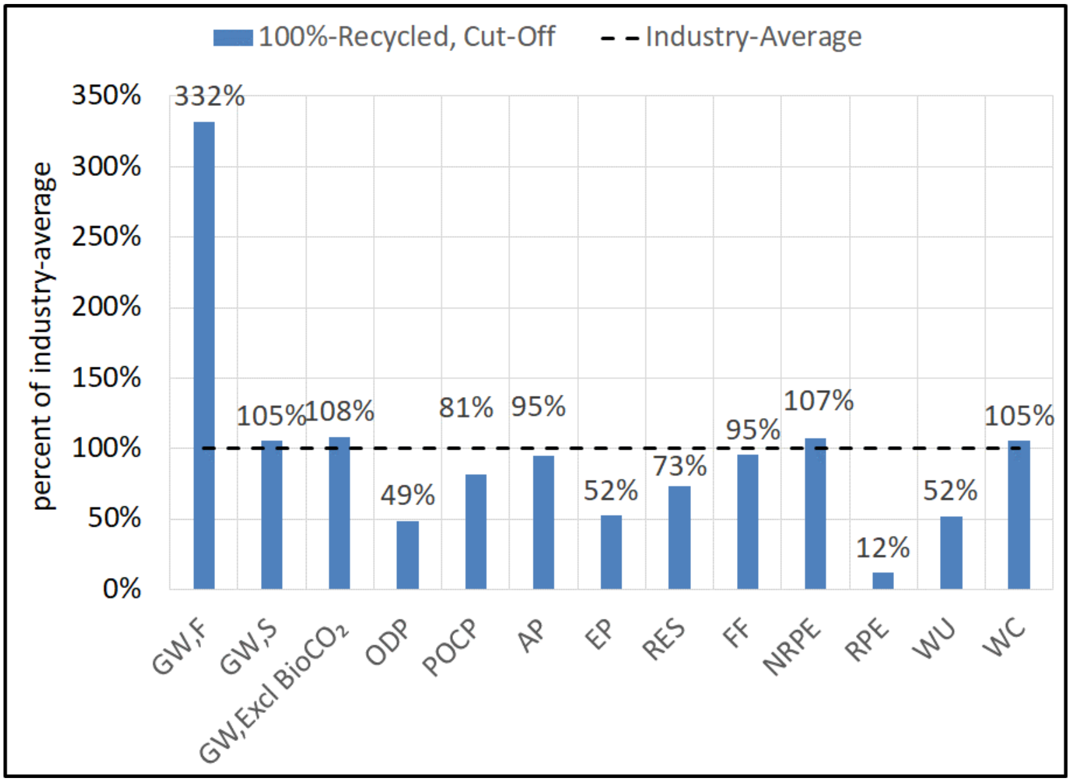


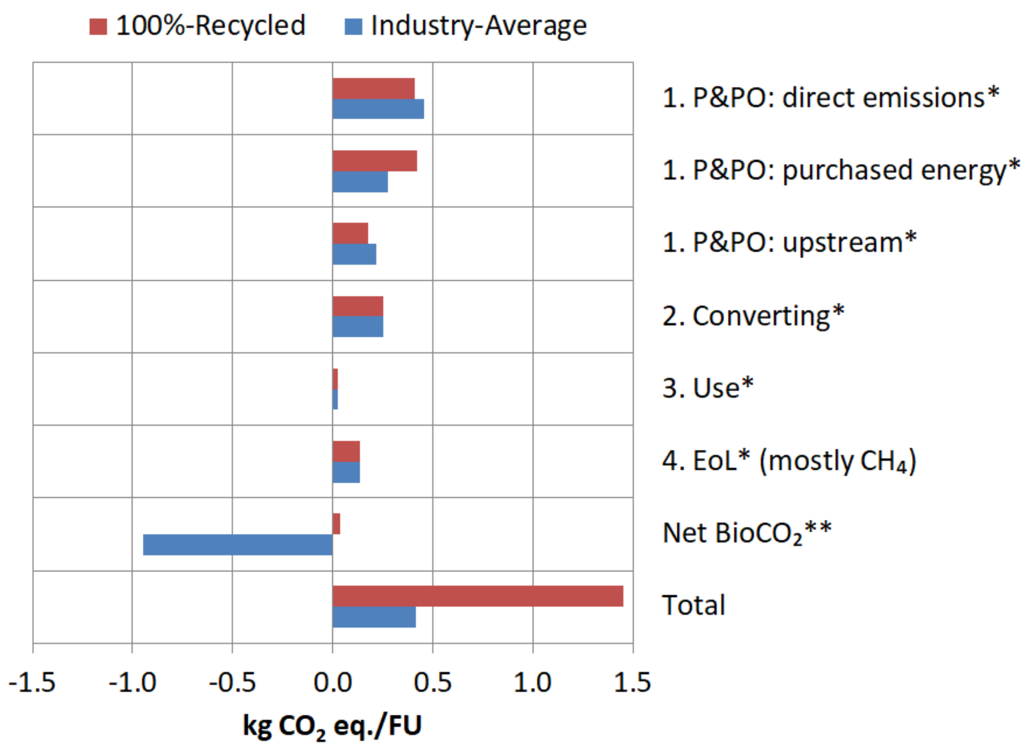
Figure 42. Impact Scores for the 100%-Recycled Product Relative to that of the Industry-Average Product (Cut-Off Method)

8.2.3.1 Global Warming

As shown in Figure 42, when applying the Cut-Off Method the global warming results are significantly higher for the 100%-recycled product than for the industry-average product when using the flow accounting approach (GW,F) and somewhat similar when using the stock change accounting approach or when ignoring biomass CO_2.

Figure 43 provides more explanation for the difference between the industry-average and 100%-recycled products for the flow accounting approach, primarily:

1) There are significantly more removals of CO_2 from the atmosphere associated with the industry-average product (due to its consumption of fresh fiber) that are not offset by emissions at the end-of-life because 89.5% the product is recovered for recycling; and
2) The 100%-recycled product consumes more purchased energy that is almost fully generated using fossil fuels.



*In this figure, P&PO means pulp and papermaking operations. The pulp and paper making life cycle stage was separated into direct emissions from pulp and paper mills (e.g., fuel combustion at containerboard mill), emissions from pulp and paper mills purchased energy, and other upstream emissions (e.g., from producing the chemicals needed in pulp and papermaking). Emissions from the four life cycle stages exclude biogenic CO_2, for which a net value is presented separately.

Figure 43. Difference in GHG Emissions between the Industry-Average and 100%-Recycled Corrugated Products (Cut-Off Method)

8.2.3.2 Ozone Depletion (ODP)

The releases of ozone-depleting substances are significantly lower for the 100%-recycled product than for the industry-average product when the Cut-Off Method is applied. This is mainly due to greater release of ozone-depleting substances associated with more biofuel combustion in producing the industry-average product.

8.2.3.3 Smog (POCP)

Smog emissions are significantly lower for the 100%-recycled product than for the industry-average product when the Cut-Off Method is applied. This is mainly because NO_x emissions are lower at pulp and paper mills that use 100%-recycled fiber than for the industry-average, most likely due to a different fuel mix.

8.2.3.4 Acidification (AP)

The results for the acidification indicator are lower for the 100%-recycled product than for the industry-average product when the Cut-Off Method is applied. This is mainly because higher amounts of acidifying substances are released from fresh fiber production process than for recycling process.

8.2.3.5 Eutrophication (EP)

The results for the eutrophication indicator are significantly lower for the 100%-recycled product than for the industry-average product when the Cut-Off Method is applied. The main explanation is that NO_x emissions relative to air and phosphorus releases to water are significantly lower at pulp and paper mills that use 100%-recycled fiber. Note, however, that phosphorus releases from pulp and paper mills are very uncertain for both the industry-average and 100%-recycled products. The effect of this uncertainty is discussed later.

8.2.3.6 Fossil Fuel Depletion (FF), Non-Renewable Primary Energy Demand (NRPE), and Renewable Energy Demand (RPE)

The difference in fossil fuel depletion and non-renewable energy demand between the industry-average and 100%-recycled product is less than 10% when the Cut-Off Method is applied. However, the 100%-recycled product consumes significantly less renewable energy than the industry-average product. Overall, the 100%-recycled product consumes less total energy than the industry-average.

8.2.3.7 Respiratory Effects (RES)

The results for the respiratory effects indicator are significantly lower for the 100%-recycled than for the industry-average product when the Cut-Off Method is applied.

8.2.3.8 Water Use (WU) and Water Consumption (WC)

Water use is significantly lower for the 100%-recycled product than for the industry-average product when the Cut-Off Method is applied. This is mainly because pulp and papermaking using recycled fiber requires less water than when using fresh fiber. However, water consumption is not significantly different for the two products. Water consumption does go up as a percentage of the intake as water use goes down. Water consumption will also increase on a volumetric basis as water use goes down because temperature management issues become more important.

8.2.4 Sensitivity Analysis

This section presents results of sensitivity analyses that have been performed on: (a) parameters that contribute significantly to the results and have significant uncertainty associated with them, and (b) methodological choices with potential effects on the results in the context of applying the Cut-Off Method. Sensitivity analyses were performed on the following aspects:

- LCIA method;
- accounting approach for biogenic CO_2;
- board mix; and
- electricity mix for 100%-recycled linerboard and medium.

Results of these sensitivity analyses are discussed in the following paragraphs.

8.2.4.1 LCIA Method

Figure 44 compares the results obtained using the TRACI and CML methods for the acidification (AP), eutrophication (EP) and smog (POCP) indicators when the Cut-Off Method is applied. This figure shows that the choice of method does not change the conclusion of the comparison.

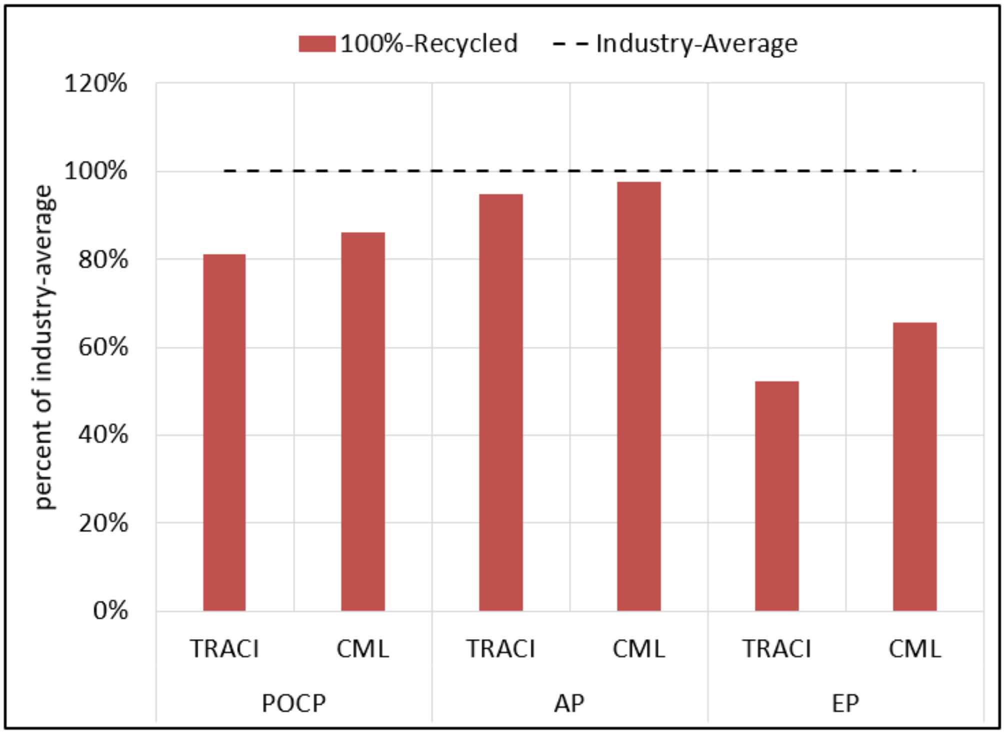


Figure 44. Results for the 100%-Recycled Product Relative to that of the Industry-Average Product: TRACI vs. CML (Cut-Off Method)

8.2.4.2 Accounting Approach for Biogenic CO_2

The effect of the accounting approach used for biogenic CO_2 on the global warming indicator results when the Cut-Off Method is applied was presented in Figure 42. When using flow accounting, the 100%-recycled product has a score for the global warming indicator that is 351% that of the industry-average, whereas the score is 105% of the industry-average score when using stock change accounting or when ignoring biogenic CO_2. This shows that, although the magnitude of the difference between 100%-recycled and industry-average varies significantly depending on the method used, the industry-average product always results in lower global warming impact.

8.2.5 Proportion of Each Individual Board Type in the Production Mix

When comparing the 100%-recycled product to the industry-average product, the ratio of linerboard to medium was kept constant, representing the fairest approach because the same product mix is compared. Another approach could have been to compare the actual industry-average corrugated product produced and used in the U.S. to the actual 100%-recycled corrugated product produced and used in the U.S (based on data from AF&PA). As shown in Table 42 above, this affects the ratio of linerboard and medium in the corrugated product. While the industry-average product produced and used in the U.S. is made of 65.9% linerboard and 34.1% corrugated medium, the 100%-recycled product produced and used in the U.S. is made of 49.8% and 50.2% corrugated medium, indicating a difference in exports of the different containerboard components.

Figure 45 shows that the board mix does not significantly affect the results except for global warming indicator (GW,F) and respiratory effect indicator (RES) when the Cut-Off Method is applied. This is because 100%-recycled linerboard and 100%-recycled medium have very similar environmental performance. From converting to end-of-life, they are assumed to have the same environmental profile. The production of 100%-recycled linerboard and 100%-recycled medium use similar quantities of fiber and of energy. Other aspects that differ between the two products, such as chemical and additive usage, are not very significant in terms of the overall environmental performance of the two products. With few exceptions, recycled linerboard and recycled medium are produced at the same facilities. The most straightforward method for a mill to allocate environmental load to the two products would be to use mass allocation, which would result in the same environmental profile for the two products on a mass basis.

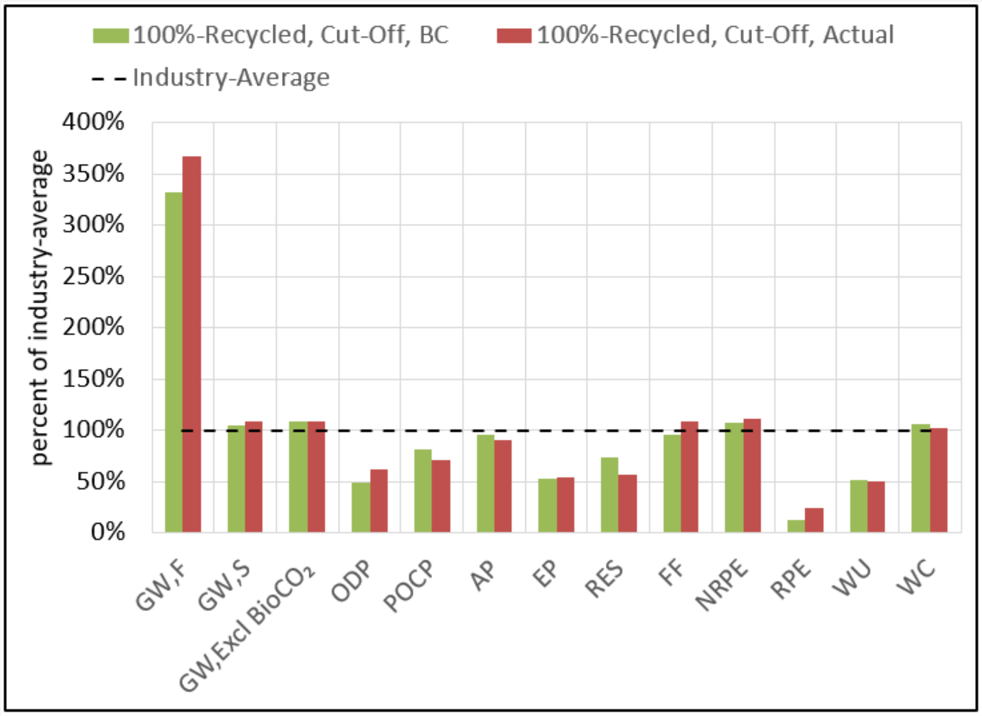


Figure 45. Effect of Board Mix on the Comparison of 100%-Recycled and Industry-Average Products (Cut-Off Method)

8.2.5.1 *Electricity Mix for 100%-Recycled Linerboard and Medium*

More than 99% of the data collected for 100%-recycled linerboard and medium was from eastern U.S. states. One effect of this is to skew the impact of the electricity mix modeled in the study.

This sensitivity analysis assesses the effect of the following electricity mix for recycled product (based on 2020 data from Fisher International):

- Recycled linerboard:
    - East: 80.8%
    - West: 15.7%
    - Texas: 3.5%
- Recycled medium:
    - East: 75.1%
    - West: 23.9%
    - Texas: 1.0%

As illustrated in Figure 46, the resulting difference in electricity mix has little or no significant effect on the results for most of indicators. A significant effect is observed only for global warming indicator (GW,F) and respiratory effect indicator (RES) when the Cut-Off Method is applied.

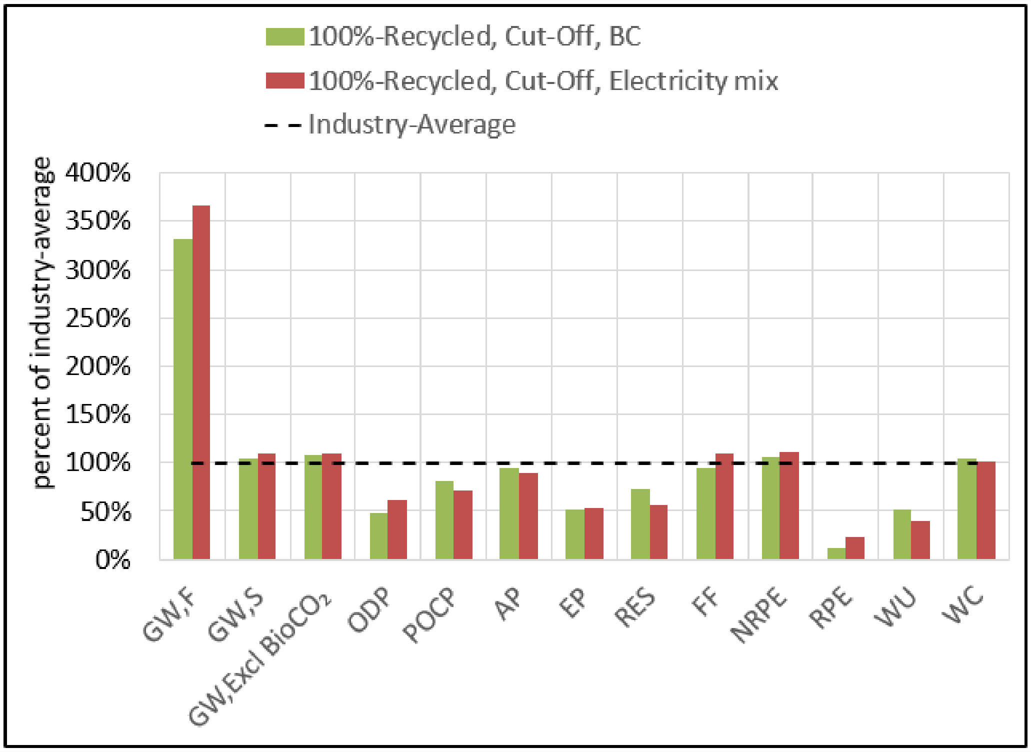


Figure 46. Effect of Electricity Mix on the Comparison of 100%-Recycled and Industry-Average Products (Cut-Off Method)

8.3 Summary

Figure 47 and Table 46 presents a summary of the results obtained for the evaluation of the environmental performance of the 100%-recycled product relative to that of the industry-average product. The results in the table reflect the following interpretations:

- For a given allocation method and a specific environmental indicator, a product was considered as having a lower score if its environmental score was lower than the other product's score by at least 10%.
- For a specific environmental indicator, a product was considered to have a lower environmental score overall if its score was lower, by both allocation methods, than the other product's score by at least 10%.
- For a specific environmental indicator, a product was considered to "probably" have a lower environmental score if its score was lower, by both allocation methods, than the other product's score by less than 10%.

The industry-average product shows a lower environmental score for the global warming indicator (flow accounting) and probably shows a lower environmental score for the other global warming indicators, fossil fuel depletion, non-renewable energy consumption, and water consumption.

The 100%-recycled product shows a lower environmental score for the renewable energy and water use indicators and probably a lower environmental score for the eutrophication indicator.

The results of comparing the industry-average and 100%-recycled products strongly depend on the allocation method for the ozone depletion, smog, acidification, and respiratory effects indicators.

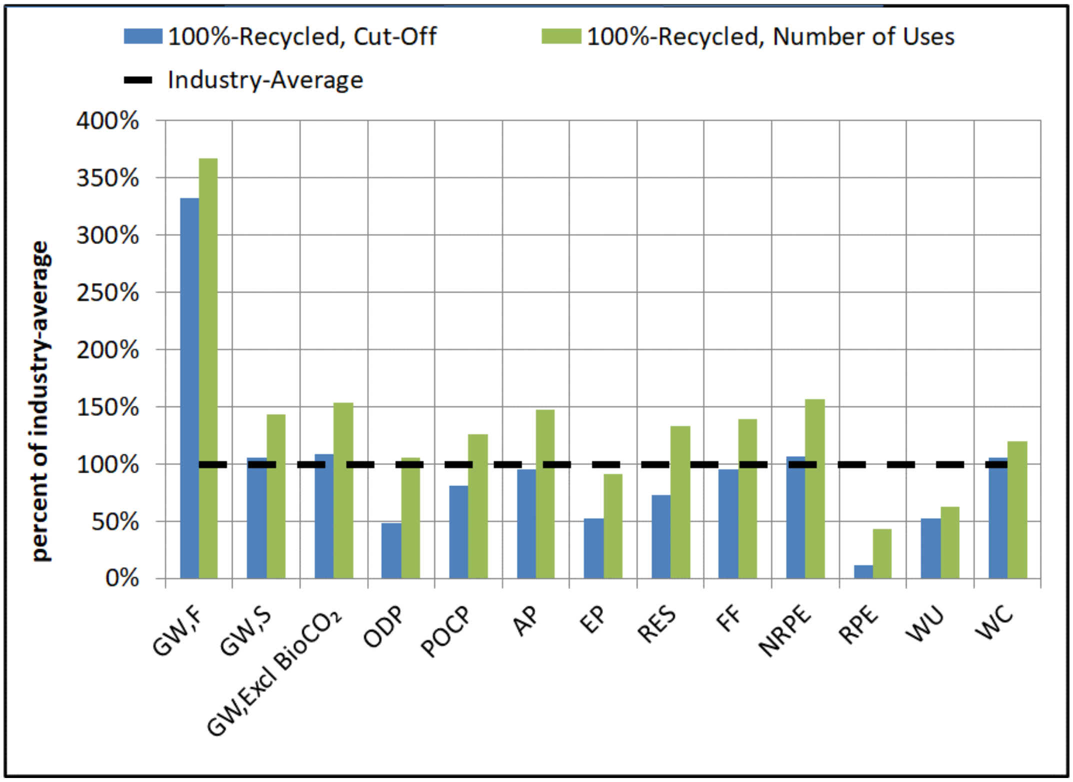


Figure 47. Implications of Using the Cut-Off vs. NOU Methods for Comparing Industry-Average and 100% Recycled Products

Table 46. Environmental Indicator Results for the 100%-Recycled Product Relative to that of the Industry-Average Product Given Two Allocation Methods for Recycling

Impact Indicator	Product with the Lower Environmental Indicator Result		
	Number of Uses Method	**Cut-Off Method**	**Overall**
Global warming, flow accounting	Industry-average	Industry-average	Industry-average
Global warming, stock change accounting	Industry-average	No significant difference observed	Probably industry-average
Global warming, excluding biogenic CO_2	Industry-average	No significant difference observed	Probably industry-average
Global warming, all indicators	Industry-average	Depends on the indicator	Probably industry-average
Ozone depletion	Industry-average	100%-recycled	Depends on the method
Smog	Industry-average	100%-recycled	Depends on the method
Acidification	Industry-average	100%-recycled	Depends on the method
Eutrophication	No significant difference observed	100%-recycled	Probably 100%-recycled
Respiratory effects	Industry-average	100%-recycled	Depends on the method
Fossil fuel depletion	Industry-average	No significant differences observed	Probably industry-average
Non-renewable primary energy demand	Industry-average	No significant differences observed	Probably industry-average
Renewable primary energy demand	100%-recycled	100%-recycled	100%-recycled
Water use	100%-recycled	100%-recycled	100%-recycled
Water consumption	Industry-average	No significant differences observed	Probably industry-average

9. EVALUATION

The evaluation phase of an LCA is intended to establish confidence in the results of the life cycle assessment. It normally includes a sensitivity check, completeness check, and consistency check, and can be supplemented with uncertainty and data quality analyses.

9.1 Sensitivity Check

Sensitivity analyses were performed for the three main objectives of this project and the results were presented in previous sections.

9.2 Completeness and Consistency Checks

The completeness check is the *"process of verifying whether information from the phases of a life cycle assessment is sufficient for reaching conclusions in accordance with the goal and scope definition"* and the consistency check is the *"process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached."* (ISO 2006b, p. 6).

In this study, most assumptions and methodological choices have been applied consistently. Sensitivity analyses were performed on methodological choices, on the parameters with relatively large uncertainty, and on potential inconsistencies. These allowed clear definition of the conditions for which the main conclusions remain valid. Hence, consistency in modeling systems in the study is considered sufficient to achieve the objectives. There were no significant data gaps, and hence the completeness of the study is considered adequate in relation to its objectives.

9.3 Uncertainty Analysis

No formal quantitative uncertainty analysis was performed in this study. However, uncertainty is important in understanding the significance of the results obtained, especially when comparisons are performed. For this reason, a qualitative analysis was undertaken. Any difference lower than 10% is unlikely to be significant (Franklin Associates 2004, Humbert et al. 2009, NCASI 2010). The results are summarized below.

9.3.1 Comparison of 2020 and 2014

The differences observed between the 2020 and 2014 LCA results for the ozone depletion, smog, eutrophication, non-renewable energy, renewable energy demand, and water consumption indicators fall below the 10% threshold. This indicates that, for these indicators, the differences observed between 2014 and 2020 are not considered meaningful. However, reductions considered meaningful were observed for the global warming using flow accounting method (-20.5%), global warming using stock change accounting method (-11.7%), smog (-27%), acidification (-26.7%), and respiratory effects (-25.7%) indicators. The positive difference between 2014 and 2020 result was observed for the fossil fuel depletion indicator (23.2%). Difference in water use was due to sampling.

9.3.2 Comparison of 100%-Recycled to Industry-Average Products

9.3.2.1 Number of Uses Method

Based on the uncertainty analysis only, the significance of the differences observed between industry-average and 100%-recycled products was not significant for the eutrophication indicator (see Figure 33).

9.3.2.2 Cut-Off Method

Based on the uncertainty analysis only, the significance of the differences observed between industry-average and 100%-recycled products was not significant for the global warming (stock change accounting and excluding biogenic CO_2), fossil fuel depletion, non-renewable energy, and water consumption indicators (see Figure 42).

9.4 Data Quality Analysis

The results of the data quality analysis were presented in the inventory phase of this LCA (see Section 4.4).

10. CONCLUSIONS AND LIMITATIONS

This study represents a comprehensive LCA of a 2020 U.S. industry-average corrugated product. The main conclusions that can be drawn from the study are discussed here.

10.1 2020 Industry-Average Product

Pulp and papermaking production (containerboard) is the main driver of the life cycle environmental performance. For all impact categories, material and energy flows from paper mills dominate the results (positively or negatively). Environmental impacts are dominated by energy demands at the mill. Bio-based energy (e.g., hog-fuel, liquor, etc.) substantially reduces the global warming contribution from mills. Converting facilities also contribute relatively significantly to most impact categories.

End-of-Life is only significant with respect to the global warming indicator results. Other life-cycle impact indicators show little or no response from the end-of-life stage. The global warming potential observed at end-of-life is mainly due to methane released from landfill operations. Sensitivity analyses clearly showed that increasing the recovery rate has the potential to improve overall environmental performance.

The global warming indicator results are highly dependent on the accounting method for biogenic CO_2. Two different accounting approaches can be used to compute the results for the global warming indicator: flow accounting, which was the main method employed in this study, and stock accounting, which was examined in a sensitivity analysis. Flow accounting is the accounting method the approach most commonly used in LCA studies. Stock change accounting is primarily used in national inventories. Another approach sometimes used in LCA is simply ignoring biogenic CO_2 when calculating the global warming indicator results to get an understanding of how non-biogenic CO_2 GHG emissions contribute to the global warming indicator. Note that this latter approach ignores any removal/storage of biogenic carbon. The effect on the global warming indicator of applying one of approach versus the other was very significant. The pulp and papermaking operations life cycle went from being an insignificant contributor to global warming when applying the flow accounting approach to a very significant contributor when applying the stock change method or ignoring biogenic CO_2. When applying the stock change accounting approach or ignoring biogenic CO_2, the contribution of end-of-life to the overall global warming results was reduced compared to when applying the flow accounting method.

10.2 Comparison of 2020 and 2014 Results

Overall, the life cycle environmental performance was improved between 2014 and 2020. The main drivers for improved environmental performance include greening of the grid, reduction in purchased energy, and further switching to natural gas (which also resulted in a significant increase in the fossil fuel depletion indicator).

The sensitivity analysis found that the changes in performance between 2014 and 2020 calculated in the study were affected in magnitude by the parameters examined in the sensitivity analysis but not in direction, indicating that the results are robust for most environmental indicators. An exception is the global warming indicator, as it can be sensitive to the relative distribution of linerboard in the board mix. The board mix for containerboard produced and used in the U.S. was estimated based on various sources of information. Errors in the mix could have significant effects on the global warming results.

10.3 Comparison of 100%-Recycled to Industry-Average Products

<u>The results of comparing the industry-average product to 100%-recycled product varied by indicator, with some results being strongly dependent on the allocation method chosen for recycling.</u>

In summary, the industry-average indicator results were lower for the global warming, acidification. And non-renewable energy indicators regardless of the allocation method used, although for the non-renewable indicator the results obtained with the Cut-Off Method showed that the difference between the two products was not significant. Results also suggest that the 100%-recycled product generates lower emissions of eutrophying substances and uses less water and renewable energy than the industry-average, although for the eutrophication indicator the results obtained with the Number of Uses Method showed that the difference between the two products was not significant. The results for the other environmental indicators (i.e., ozone depletion, smog, eutrophication, respiratory effects, fossil fuel depletion) depend on the allocation method.

Although 100%-recycled corrugated medium production was under-represented by the survey data used in the study, a sensitivity analysis showed that this was unlikely to affect the general findings described above.

10.4 Limitations and Recommendations

With regards to the 2020 LCA results the main limitations are as follows.

- 100%-recycled products were relatively less well represented in the data collected, especially 100%-recycled corrugated medium. Note that, when developing the industry-average, the actual board mix was used, eliminating the bias due to under-represented board types in the industry-average. In addition, no industry survey can ever pull in 100% of the operating facilities, and that anomalies across any sector for which an LCA is being conducted may be either obscured or magnified due to the universe of mills that provide survey responses. Future LCAs should focus on improving the representation of 100% recycled corrugating medium while addressing potential biases by including a bigger sample of facilities.
- There were small discrepancies in mass/carbon balances. Carbon balances were adjusted to be conservative.
- The data collection was performed in a way that ensured that any flow contributing to more than 1% of the mass inputs of those processes was included, except for chemicals. Knowledge gained during the previous LCA efforts, in terms of the point after which additional data do not add measurable benefit to the robustness of the final LCA results, justified the assessment to include only those chemicals contributing more than 10% of

> the total dry mass of chemicals used in each containerboard component. In this manner, no chemicals with significant individual contribution to any environmental indicator (i.e., > 5%) would be ignored. In addition, the mills were asked to report the total mass of "other fillers", which would account for a large proportion of the missing chemicals. Future LCAs should revisit the list of chemicals included in data collection efforts to ensure there are no new chemicals used by the industry that should not be ignored.

In terms of the yearly comparisons, the limitations described above also apply. The 2020 data were scaled to match the board mix actually produced, as was done previously for the 2014 and 2010 data. This was not possible using 2006 data because of the way the data were collected at that time.

In terms of the 100%-Recycled/industry-average comparison, the limitations described above also apply. In addition, differences in board types’ representativeness were also identified as a potential shortcoming. The general conclusions of the comparison were shown not to be significantly affected (less than 10% difference) by this limitation.

11. CRITICAL REVIEW

A critical review was undertaken for this study to ensure it is completed to the requirements of ISO 14040 Series Standards and industry best practices. Some aspects of this study are comparative, making the peer review even more critical. However, because the study was essentially a repetition of one undertaken in previous years, only one person reviewed it. Lindita Bushi, PhD, from the Athena Sustainable Materials Institute was commissioned to undertake the critical review in accordance with ISO 14040/44 (2006).

The review process consisted of the following steps:

1. Review and comment on the draft final report;
2. Discuss issues with study CPA and NCASI; and
3. Review of the updated final report.

The details of the final peer review can be found on the next page and the details in Appendix I.

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Critical Review Statement of 2020 Life Cycle Assessment of U.S. Average Corrugated Product LCA Report

Commissioned by:	Corrugated Packaging Alliance (CPA) A joint venture of American Forest & Paper Association (AF&PA) Fibre Box Association (FBA) AICC, The Independent Packaging Association (AICC), and TAPPI
Conducted by:	National Council for Air and Stream Improvement, Inc., and Anthesis
External Reviewer:	Lindita Bushi, Ph.D. Athena Sustainable Materials Institute
References:	ISO 14044:2006/Amd.1:2017/Amd.2:2020 – Environmental Management – Life Cycle Assessment – Requirements and Guidelines https://www.iso.org/standard/38498.html?browse=tc ISO 14040:2006/Amd.1:2020 – Environmental Management – Life Cycle Assessment – Principles and framework https://www.iso.org/standard/37456.html ISO/TS 14071:2014 — Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006 https://www.iso.org/standard/61103.html?browse=tc

Scope of the Critical Review

In accordance with ISO 14044:2006, section 6.1, the goal of the Critical Review was to assess whether:

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed as an external reviewer following ISO 14044:2006, section 6.2.

The reviewer confirms that she has been independent in her role as reviewer per the ISO 14044 requirements and has no conflicts of interest regarding this review. The reviewer has signed and submitted a *self-declaration form of reviewer independence and competencies* to CPA in accordance with ISO/TS 14071:2014.

The review was performed exclusively on the LCA study report and any supplementing information in the public domain.

This review statement is only valid for this specific report titled "2020 Life Cycle Assessment of U.S. Average Corrugated Product Full Report" and dated October 2023.

Critical Review Process

The critical review was conducted between 26/07/2023 and 06/11/2023 (delivery of the critical review statement).

The review was conducted by exchanging comments and responses using a review template (an Excel spreadsheet) based on Annex A of ISO/TS 14071:2014. There were two formal rounds of comments.

The rigorous review process improved the LCA study, particularly regarding technical data consistency and transparency (mass and carbon balances), industry-average data geographical representativeness, and by adding limitations and recommendations to the study conclusions.

The overall review was conducted professionally and constructively. All comments were adequately addressed, and any open issues were successfully resolved. No conflicting opinions were held by any of the involved parties (external reviewer, LCA practitioners, and commissioner) upon finalization of the review. Upon request, a copy of the review report containing all comments and responses is available from CPA.

Critical Review Evaluation and Conclusion

The 2020 Life Cycle Assessment of U.S. Average Corrugated Product LCA Report is very well-scoped and adequately supports the study goals with the primary goal being the education of customers and stakeholders about the potential environmental impacts of the industry's corrugated packaging produced in 2020. The study shows a very high level of market relevance and LCA methodological proficiency combined with adequate data for the reference year 2020 to ensure the accuracy of the potential LCA results.

Based on the final study report and scope of the critical review, it can be **concluded** *that the methods used to carry out the LCA are consistent with the international standard ISO 14044, that they are scientifically and technically valid, that the data used are appropriate and reasonable in relation to the goal of the study, and that the interpretations reflect the limitations identified and the goal of the study. The final study report is considered sufficiently transparent and consistent.*

ISO 14044, section 5.2 requires that a third-party report be publicly available to any third party other than the practitioner or the commissioner. Confidential content may be removed from the report prior to sharing it with third parties.

The reviewer signs this review statement as an individual expert. Her signature does not imply the affiliated organization's endorsement of the study's scope or results.

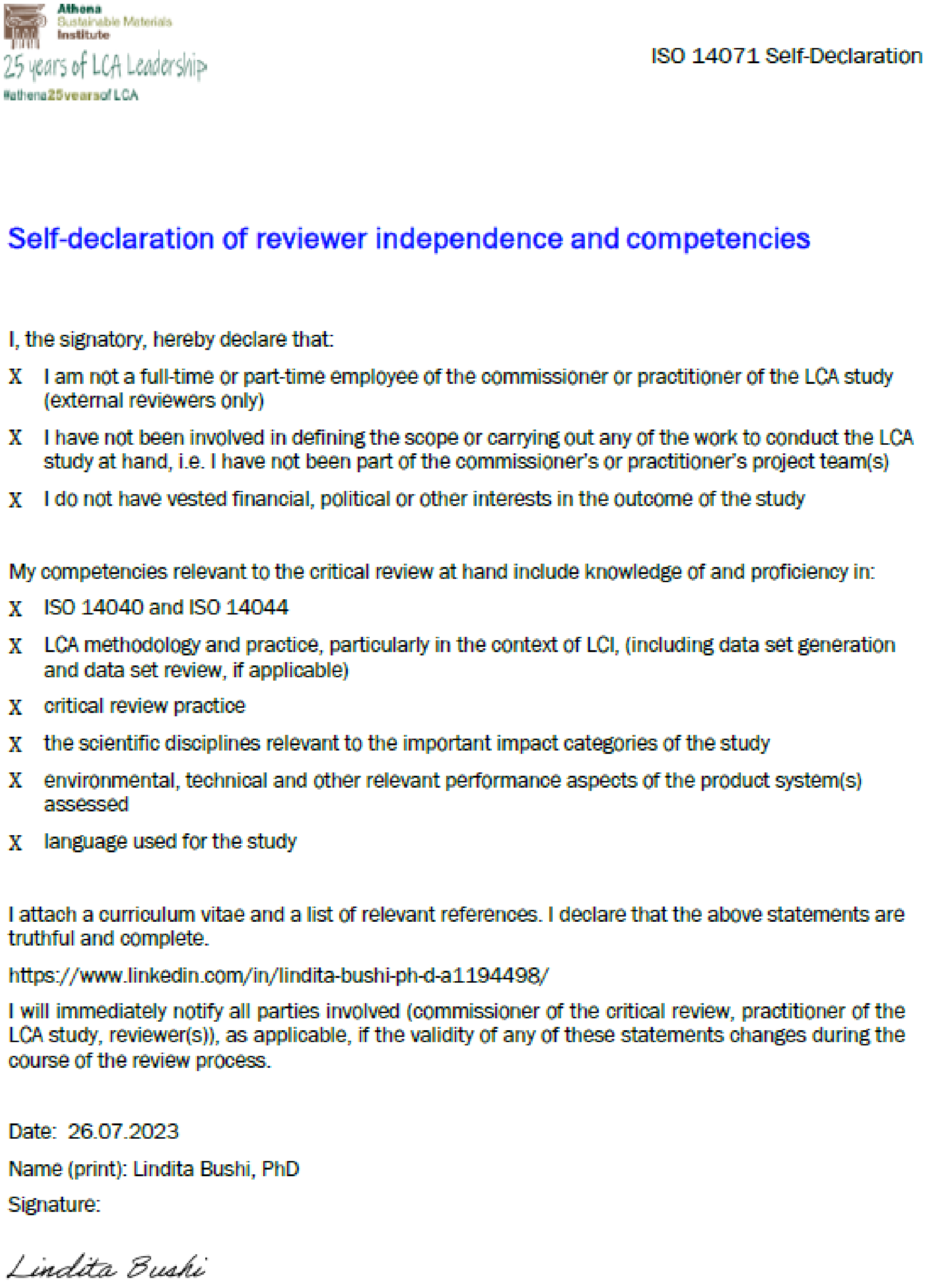
The reviewer appreciates the professional responsiveness of NCASI and Anthesis LCA teams to all technical queries and comments and that of all parties involved in the review process.

Respectfully,

Lindita Bushi

Lindita Bushi, Ph.D.
Athena Sustainable Materials Institute

Valid as of November 06, 2023



Athena Sustainable Materials Institute
25 years of LCA Leadership
#athena25yearsofLCA

ISO 14071 Self-Declaration

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

X I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)

X I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)

X I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

X ISO 14040 and ISO 14044

X LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable)

X critical review practice

X the scientific disciplines relevant to the important impact categories of the study

X environmental, technical and other relevant performance aspects of the product system(s) assessed

X language used for the study

I attach a curriculum vitae and a list of relevant references. I declare that the above statements are truthful and complete.

https://www.linkedin.com/in/lindita-bushi-ph-d-a1194498/

I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 26.07.2023

Name (print): Lindita Bushi, PhD

Signature:

Lindita Bushi

APPENDICES

A. DISCUSSION OF ISO 14044 OPTIONS FOR ALLOCATION

In this appendix, the general recommendations of the ISO 14044 Standard on LCA (ISO 2006b, p. 14) regarding co-product and open-loop recycling allocation are summarized. The ISO 14044 Standard specifies the following requirements for all allocation situations.

> *"The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure.*
>
> *The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.*[23]
>
> *Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.*
>
> *Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g., intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system."*

This last requirement means that the same allocation procedure shall be applied to both the production and use of recovered fiber.

The ISO Standard proposes different strategies that can be used to resolve co-product and recycling allocation problems. These are discussed below.

A.1 Co-Product Allocation

The ISO 14044 Standard on LCA (ISO 2006b) provides the following hierarchy of strategies for co-products :

1) Avoid allocation through
    a. System subdivision, or
    b. System expansion,
2) Perform allocation using an underlying physical relationship, and
3) Perform allocation using another relationship.

Strictly speaking, the hierarchy in the ISO 14044 Standard requires that, whenever possible, system subdivision and expansion strategies must be selected. Practically speaking, the selection of an adequate approach depends on the goal of the study, the available data and information, and the type of the shared process to be allocated (Ekvall and Weidema 2004, European Commission - Joint Research Centre - Institute for Environment and Sustainability (EC-JRC-IES) 2010, Tillman 2000, Werner 2005b). The LCA ISO series (International Organization for

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[23] This is often referred to as the modularity requirement.

Standardization (ISO) 2006a, b) also recognizes that the decision context and the intended application should be considered when defining the product system studied but has been criticized for not accounting for various application approaches in its allocation hierarchy (Ekvall and Finnveden 2001, Ekvall and Tillman 1997, Ekvall and Weidema 2004, Werner 2005b).

A.2 Recycling

The ISO 14044 Standard (International Organization for Standardization (ISO) 2006b) specifies that the hierarchy for co-product allocation also applies to recycling, especially for the recovery processes. However, additional elaboration may be required because recycling *"may imply that the inputs and outputs associated with unit processes for* ***extraction and processing of raw materials*** *and* ***final disposal of products*** *are to be shared by more than one product system"* (International Organization for Standardization (ISO) 2006b). In other words, the recovery processes are not the only processes shared between different product systems. Another reason for recycling allocation to potentially require additional elaboration is that it *"may change the inherent properties of materials in subsequent use"* (International Organization for Standardization (ISO) 2006b).

Several allocation approaches can be applied to open-loop recycling. As mentioned, the first approach in the ISO 14044 hierarchy for co-products is to avoid allocation by dividing or expanding the system boundaries. Another way to avoid allocation, in a manner that is specific to recycling allocation problems, is to approximate an open-loop system with a closed-loop system. In doing so, it is assumed that the use of recovered material displaces the use of fresh fiber materials. The ISO Standard allows for this only in cases "*where no changes occur in the inherent properties of the recycled material*[24]*"* (International Organization for Standardization (ISO) 2006b).

In cases where allocation cannot be avoided, the ISO Standard (International Organization for Standardization (ISO) 2006b) recommends application of an allocation procedure for the shared unit processes that use, in order of preference, the following as the basis for allocation, where feasible:

- Physical properties (e.g., mass);
- Economic value (e.g., market value of the scrap material or recycled recovered in relation to market value of primary material); or
- Number of subsequent uses of the recovered material.

A.3 Relation between the Study Objective and the Choice of an Allocation Strategy

The LCA ISO series (ISO 2006a, b) also recognizes that the decision context and the intended application should be considered when defining the product system studied and mentions two application approaches for LCA that have been developed in recent years:

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[24] The ISO Standard uses the term "recycled material" to designate a type of secondary raw material. This terminology can be confusing. Hence, in this document, "recovered material" will be used instead.

1) "one which assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product, and
2) one which studies the environmental consequences of possible (future) changes between alternative product systems."

These have been called Accounting LCA and Change-Oriented LCA, respectively, along with a variety of other monikers. Although the ISO 14044 Standard recognizes that "the scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study," it does not provide any guidance on how the allocation hierarchy should be adapted in this context. In the literature, there is general agreement that system subdivision always applies but that system expansion is better suited to change-oriented LCAs (e.g., Baumann 1996, Baumann and Tillman 2004, Ekvall 1999, Ekvall et al. 2005, Ekvall and Weidema 2004, Werner 2005a).

B. CARBON CONTENT AND MASS BALANCES

B.1 Carbon Contents

This section summarizes the calculation of carbon contents for containerboard and corrugated products.

B.1.1 Containerboard

The carbon content of industry-average containerboard ($CC_{CB,IA}$) was estimated as follows:

$$CC_{CB,IA} = \left(1 - F_{PA,IA}\right) \times CC_F + Q_{St,CB,IA} \times CC_{St} = (1 - 0.00667) \times 0.5 + 0.0049 \times 0.444 = 0.496\ kg/kg$$

Where $F_{PA,IA}$ is the fraction of the total mass of containerboard that is from papermaking additives in industry-average containerboard (aluminum sulfate, strength agent, starch and other fillers); CC_F is the carbon content of fiber, $Q_{St,CB,IA}$, the quantity of starch in industry-average containerboard; and CC_{St} is the carbon content of starch. Carbon in other additives was neglected. All units are kg per kg of containerboard.

Similarly, it was possible to calculate the carbon content of 100%-recycled containerboard ($CC_{CB,REC}$):

$$CC_{CB,REC} = \left(1 - F_{PA,REC}\right) \times CC_F + Q_{St,CB,REC} \times CC_{St} = (1 - 0.00804) \times 0.5 + 0.0159 \times 0.444 = 0.495\ kg/kg$$

Where $F_{PA,REC}$ is the fraction of the total mass of containerboard that is from papermaking additives in 100%-recycled containerboard (aluminum sulfate, calcium carbonate, sizing agent, soda, sodium carbonate, strength agents, retention aids, etc.); CC_F is the carbon content of fiber; $Q_{St,CB,REC}$ is the quantity of starch in 100%-recycled containerboard; and CC_{St} is the carbon content of starch. Carbon in other additives was neglected. All units are kg per kg of containerboard.

B.1.2 Corrugated Product

A carbon balance was used to calculate the carbon content of the corrugated product ($CC_{CP,2014}$):

$$Q_{CB,IA} \times CC_{CB,IA} + Q_{St,CP} \times CC_{St} = Q_{CP} \times CC_{CP} + Q_L \times CC_L = Q_{CP} \times CC_{CP} + Q_L \times CC_{CP}$$

$$CC_{CP,IA} = \frac{Q_{CB,IA} \times CC_{CB,IA} + Q_{St,CP} \times CC_{St}}{Q_{CP,2014} + Q_L} = \frac{1.09 \times 0.496 + 0.034 \times 0.444}{1 + 0.09} = 0.494\ kg/kg$$

Where $Q_{CB,IA}$ is the quantity of industry-average containerboard (in kg/kg); $CC_{CB,IA}$ is the carbon content of the industry-average containerboard; $Q_{St,CP}$ is the quantity of starch used in industry-average corrugated product; CC_{St} is the carbon content of starch; Q_{CP} is the quantity of corrugated product; Q_L is the quantity of converting losses; and CC_L is the carbon content of losses. Converting losses are a mixture of unconverted containerboard and trimming from corrugated product, but are mostly made of the latter. For this reason, it was assumed that the carbon content of losses was the same as that of the corrugated product (i.e., $CC_L = CC_{CP,2014}$). Carbon in other additives was neglected. All units are kg per kg of containerboard.

B.2 Mass Balances

Three types of mass balance checks were performed: a fiber balance check, a carbon balance check, and a water balance check. Given that they are using the same dataset, mass balances were checked at the industry-average level.

B.2.1 Fiber Balance

First, it was verified using standard yield values that the quantity of fiber was sufficient for manufacturing the quantity of pulp reported by the mills. As illustrated in Table 47, the fiber input falls within the expected range.

Table 47. Fiber Balance for the Industry-Average Containerboard Production

Fiber material	**Quantity of fiber (kg/kg CP)**	**Typical yield (kg pulp/kg fiber)**	**Quantity of pulp/product (kg)**
Pulpwood*	1.03	0.53 (0.49-0.67)**	0.55 (0.50-0.69)
Recovered fiber	0.60***	0.90 (0.85-0.95)	0.54 (0.51-0.57)
		Total pulp, calculated (kg/kg CP)	*1.09 (1.01-1.26)*
		Total pulp, reported (kg/kg CP)	*1.04*
		Discrepancy [(calculated-reported)/reported]	***4.8% (-2.9% to 21%)***

**Chips and logs not including self-generated hogged fuel from manufacturing residues. **Estimated weighted average of kraft (0.485) and semichemical (0.70). ***Based on raw data, corrected to 0.62 to close carbon balances.*

B.2.2 Carbon Balance

Second, the carbon balance was checked, as depicted in Table 48. This table shows a 3.8% difference between outputs and inputs of carbon. This difference may be due to:

- Imprecision in some of the carbon contents (i.e., recovered pulp, recovered fiber, WWTP residuals, and black liquor);
- Carbon content in other wastes; or
- Real discrepancies in the data collected.

Although there is more uncertainty in carbon content and associated carbon releases from biomass fuels, to be conservative, the carbon balance was forced to close by increasing total fiber input.

Table 48. Carbon Balance for the 2020 Industry-Average Containerboard Production

Carbon Input	**Quantity as Obtained through Data Collection and Assumptions**		**Carbon Output**	**Quantity as Obtained through Data Collection and Assumptions**	
	kg/kg CP	**kg C/kg CP**		**kg/kg CP**	**kg C/kg CP**
Wood inputs (logs and chips)	0.979 (1.03)*	0.489 (0.517)*	Containerboard	1.09	0.542
Recovered fiber	0.604 (0.613)*,**	0.298 (0.303)*	Combustion of self-generated manufacturing hogged fuel	0.0982	0.0491
Fresh fiber pulp	0.001	0.000	Combustion of black liquor	0.536	0.188
Recovered pulp	0.003	0.002	Combustion of hogged fuel other than self-generated manufacturing	0.0791	0.0395
Hogged fuel, not including self-generated manufacturing	0.079	0.040	Residuals burned for energy or disposed of	0.0922	0.0452
Starch		0.002	Total carbon output		0.864
Total input carbon input		0.831	***Discrepancy [(in-out)/out]***		***-3.8%***

**Corrected value. **Difference between this number and 0.62 reported elsewhere is due to rounding.*

B.2.3 Water Balance

Finally, for containerboard mills, mass balances were used to close the water balance. Data were collected for:

- water intake (aggregated cooling and process);
- effluent (process only);
- water in raw materials; and
- water in product.

The total of cooling water output and evaporation was assumed to be equal to the difference between inputs and outputs of water:

$$\begin{aligned} Difference &= Cooling\ water_{OUT} + Evaporation \\ &= Water\ intake + Water\ in\ raw\ material - Effluent - Water\ in\ product \end{aligned}$$

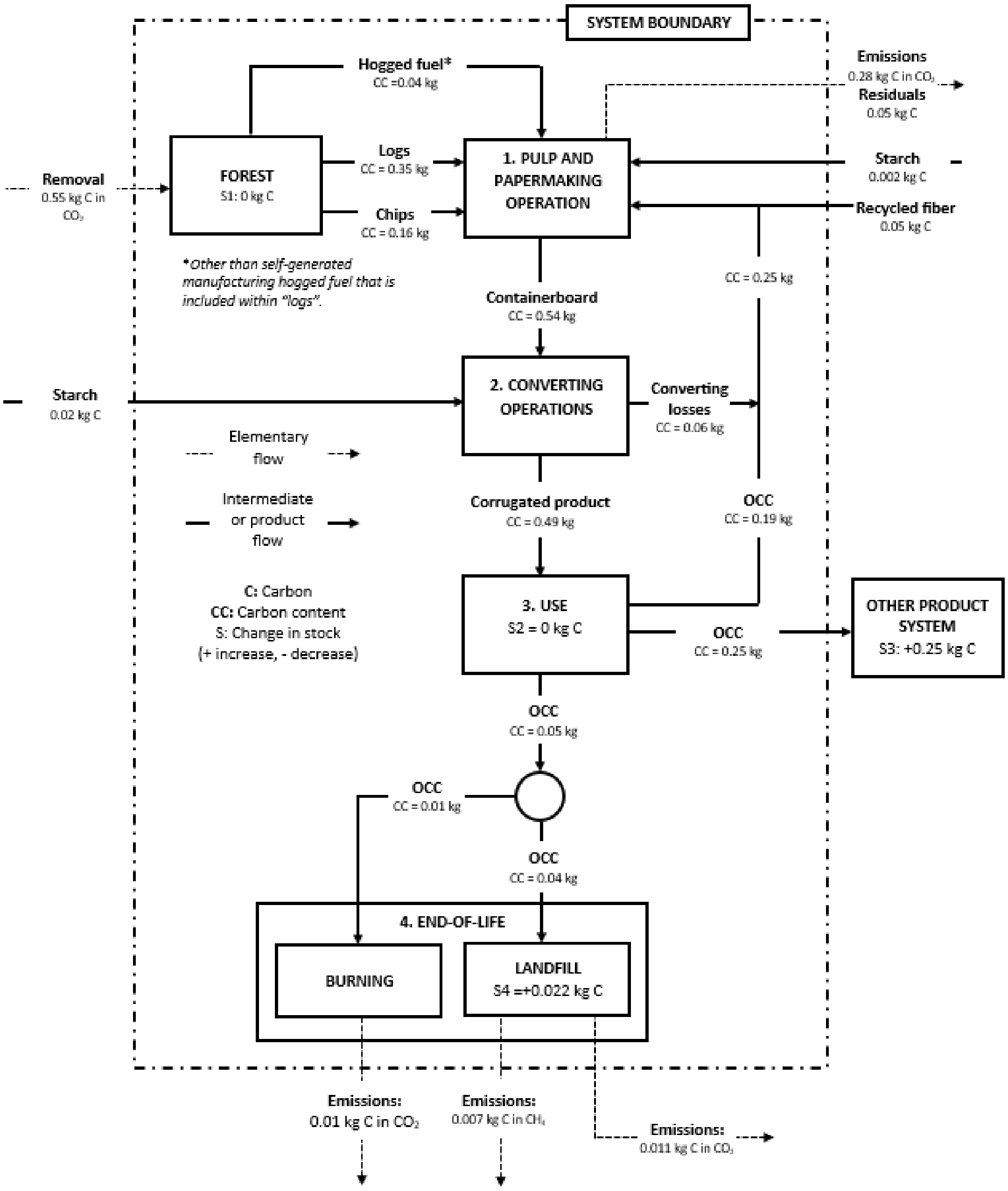
The quantity of water evaporated was estimated using NCASI data (2008, Tables 2.12, 3.6 and 3.10) and the cooling water output was calculated by difference.

B.2.4 Converting

Mass balances were also performed for converting facilities, by plant types. For confidentiality reasons, these are not presented here. However, data indicated some small discrepancies. Although the data were accepted from a QA perspective, mass balance errors for converting plants would have a direct effect on the main reference flows and hence on the study results. For this reason, it was decided to correct the mass balance for modeling purposes. A conservative approach was taken, in that the amount of containerboard or sheet input in each of the facility types was increased to close the balance. This approach is also the most aligned with the existing knowledge on typical conversion losses (i.e., between 3 and 10%).

B.2.5 Overall Biogenic Carbon Balances

Figure 48 and Figure 49 present the life cycle carbon balance for the industry-average and 100%-recycled products. For simplification, in these diagrams, all recycled fiber is depicted as OCC although there are other sources of recycled fiber used in the processes. Only major flows of carbon are depicted. Other minor flows (e.g., removals and emissions associated with purchased pulp) are not depicted for simplicity but were included in the study.

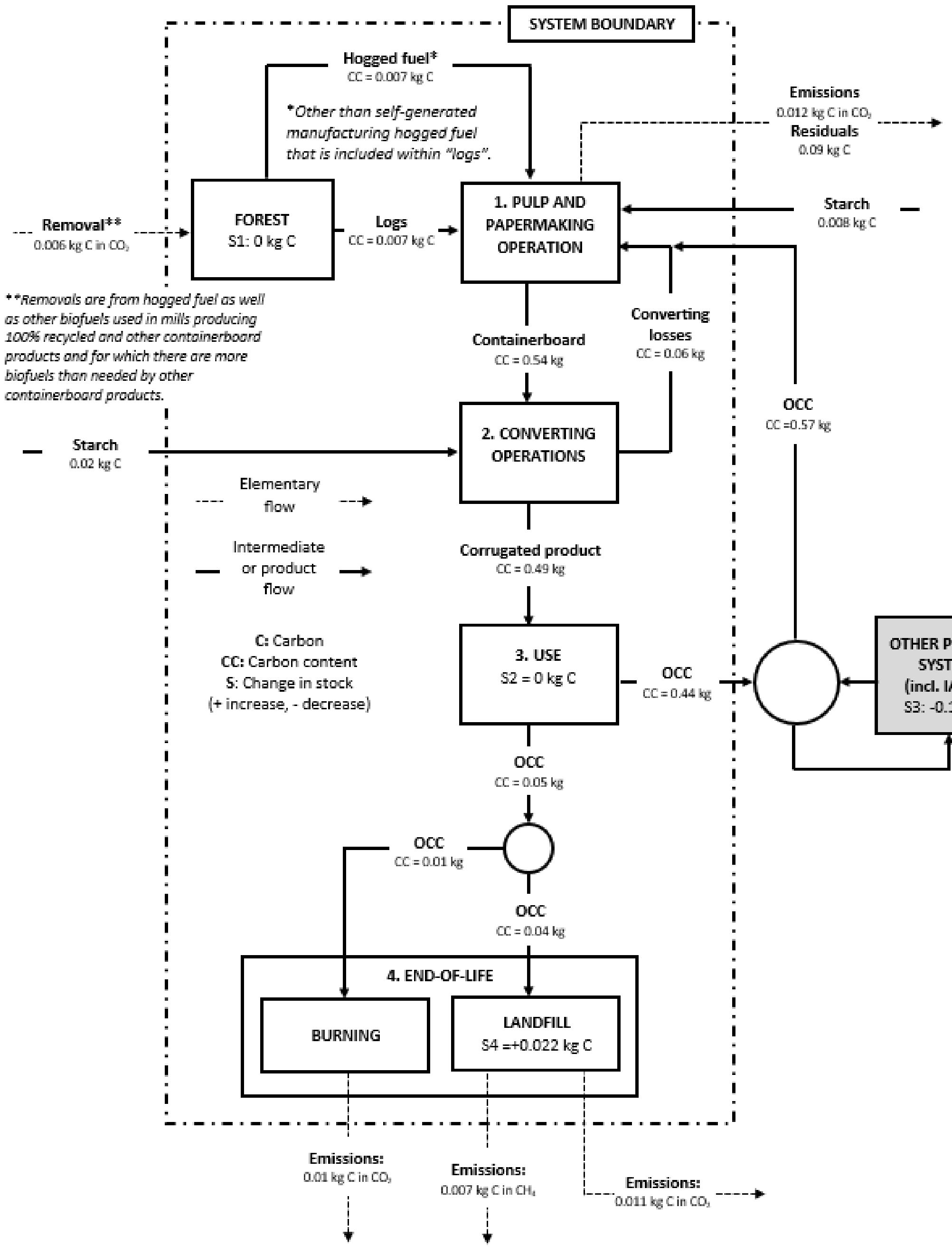


Carbon Balance:
Inputs = Outputs + Change in stocks
Inputs = 0.55 + 0.02 +0.05 + 0.002 = 0.62 kg C
Outputs + Change in stocks = 0.28 + 0.05 + 0.25 + 0.01 + 0.007 + 0.011 + 0.022 = 0.63 kg C (difference due to rounding)

Impact of Biogenic CO_2, Flow Accounting (F)
Considers flows of CO_2 to and from the atmosphere (i.e., elementary flows) occurring from unit processes within the system boundary.
F = Emissions - Removals
F = (0.28 + 0.05 + 0.01 + 0.007 + 0.011) – 0.55 = -0.20 kg C

Impact of Biogenic CO_2, Stock Accounting (S)
Considers change in stocks of carbon from unit processes within the system boundary.
S = - (S1 + S2 + S4)
S = - (0 + 0 + 0.022) = -0.022 kg C

Figure 48. Cradle-to-Grave Carbon Balance: Industry-Average Product



Carbon Balance: Inputs = Outputs + Change in stocks (within system boundary) Inputs = 0.006 + 0.02 + 0.57 + 0.008 = 0.60 kg C Outputs + Change in stocks = 0.012 + 0.09 + 0.01 + 0.007 + 0.011 + 0.44 + 0.022 = 0.59 kg (difference due to rounding)	
Impact of Biogenic CO_2, Flow Accounting (F) Considers flows of CO_2 to and from the atmosphere (i.e., elementary flows) occurring from unit processes within the system boundary. F = Emissions - Removals F = 0.012 + 0.09 + 0.01 + 0.007 + 0.011 - 0.006 = 0.12 kg C	**Impact of Biogenic CO_2, Stock Accounting (S)** Considers change in stocks of carbon from unit processes within the system boundary. S = - (S1 + S2 + S4) S = - (0 + 0 + 0.022) = - 0.022 kg C

Figure 49. Cradle-to-Grave Biogenic Carbon Balance: 100%-Recycled Product

C. DETAILED DATA SOURCES

Table 49 lists the generic datasets used in the study.

Table 49. List of Datasets Used in the Study

FIBER			
Fiber name	**Database**	**Specific dataset**	**Comment**
Logs, Northern Hardwood	U.S. LCI	Pulpwood, hardwood, average, at forest road, NE-NC/RNA	
Logs, Southern Hardwood	U.S. LCI	Pulpwood, hardwood, average, at forest road, NE-NC/RNA	No data available for southern hardwood pulpwood, northern used as a proxy
Logs, Southern Softwood	U.S. LCI	Softwood logs with bark, harvested at average intensity site, at mill, US SE/US	Without transportation
Chips, Northern Hardwood	U.S. LCI	Wood chips, hardwood, green, at sawmill, NE-NC/kg/RNA	
Chips, Southern Hardwood	U.S. LCI	Wood chips, hardwood, green, at sawmill, NE-NC/kg/RNA	No data available for southern hardwood chips, northern used as a proxy
Chips, Northern Softwood	U.S. LCI	Wood chips, softwood, green, at sawmill NE-NC/kg/RNA	
Chips, Southern Softwood	U.S. LCI	Pulp chips, at sawmill, US SE/kg/US	
Recovered Paper, Mixed	N/A	Transportation only	
Recovered Paper, Corrugated	N/A	Transportation only	
Recovered Paper, Pulp Substitutes	N/A	Transportation only	
Recovered Paper, High-grade Deinking	N/A	Transportation only	
Purchased BKMP	NCASI	NCASI 2006/2007 bleached kraft market pulp dataset	
Purchased UBKMP	EI	Sulphate pulp, unbleached, at plant/RER	
Purchased RNDI	EI	Paper, recycling, no deinking, at plant/RER	No data for pulp, paper used as a proxy

(Table continued next page.)

Table 49. (Cont'd)

CHEMICALS			
Chemical name	**Database**	**Specific dataset**	**Comment**
Adhesive	GaBi	EU-27: Starch glue (for paper/cardboard)	
Aluminium chloride	EI	Chemicals inorganic, at plant/GLO	
Aluminum sulfate	GaBi	US: Aluminium sulphate (estimation)	
Borax	U.S. LCI	Sodium borates, at plant/US	
Coatings	EI	Coating powder, at plant/RER	
Dispersant	EI	Pitch dispersants, in paper production, at plant/RER	
Ink	GaBi	US: Polyacrylate ink (estimation)	
Other fillers	Literature	Precipitated calcium carbonate used as a proxy for all other fillers	
Quicklime	U.S. LCI	Quicklime, at plant /US	
Soda	U.S. LCI	Soda, powder, at plant /US	Includes soda powder, soda ash and sodium carbonate
Sodium hydroxide	U.S. LCI	Sodium hydroxide, production mix, at plant/kg /RNA	
Starch	GaBi	US: Dried starch (corn wet mill) (economic allocation)	
Strength agents	GaBi	DE: Polyacrylamide (anionic) (solid)	Polyacrylamide is one type of strength agent, used as a proxy for all
Sulfuric acid	U.S. LCI	Sulfuric acid, at plant/RNA	
Wax	GaBi	EU-27: Wax/Paraffins at refinery	
FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Purchased Hogged Fuel, Logging Residues	U.S. LCI/US, NCASI	Forest residue, processed and loaded, at landing system/RNA, NCASI combustion emissions	

(Table continued next page.)

Table 49. (Cont'd)

FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Purchased Hogged Fuel, Manufacturing Residues	U.S. LCI/US, NCASI	Bark, at sawmill, US SE/kg US, NCASI combustion emissions	
Self-Generated Hogged Fuel, Logging Residues	U.S. LCI/US, NCASI	Forest residue, processed and loaded, at landing system/RNA, NCASI combustion emissions	
Self-Generated Hogged Fuel, Manufacturing Residues	NCASI	NCASI combustion emissions	
Spent Liquor Solids	NCASI	NCASI combustion emissions	
Self-Gen Hydroelectricity	EI	Electricity, hydropower, at run-of-river power plant/RER	
Non-Recyclable Paper	EI	Disposal, paper, 11.2% water, to municipal incineration/CH	
Other biomass	U.S. LCI/US, NCASI	Bark, at sawmill, US SE/kg/US, NCASI combustion emissions	
Sludge	NCASI	NCASI combustion emissions	
Coal	U.S. LCI	Bituminous coal, combusted in industrial boiler /US	
Distillate Fuel Oil (#2)	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for DFO combustion
Gasoline	U.S. LCI	Gasoline, combusted in equipment/US	
Kerosene	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for kerosene combustion
Liquid Propane Gas	U.S. LCI	Liquefied petroleum gas, combusted in industrial boiler/US	

(Table continued next page.)

Table 49. (Cont'd)

CHEMICALS			
FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Natural Gas	U.S. LCI	Natural gas, combusted in industrial boiler/m3/RNA	
Other Fuel/Other Fuel 1	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for other fuels
Petcoke	U.S. LCI/U.S. EPA	Bituminous coal, combusted in industrial boiler/US,	With coal replaced by petcoke and GHG emissions modeled after U.S. EPA (2010)
Residual Fuel Oil (#5,6)	U.S. LCI	Residual fuel oil, combusted in industrial boiler/US	
Rubber Tire Chips	Literature (U.S. EPA 1997)		
Purchased electricity	U.S. LCI/ EI	See more details in Section 4.2.3.	
Purchased steam	U.S. LCI	See more details in Section 4.2.3.	Steam mix obtained from the mills purchasing steam (mostly coal)
WASTE MANAGEMENT			
Name	**Database**	**Specific dataset**	**Comment**
Residuals, landfilled	NCASI	N/A	
Residuals, land applied	EI	N/A	
Residuals, burned	NCASI	N/A	Assumed to be included in combustion emissions
Sludge, ash, other waste, other beneficial	N/A	N/A	Ignored
Effluent to river	NCASI	N/A	
Effluent to municipal treatment	GaBi	EU-27: Waste water treatment (slightly organic and inorganic contaminated) PE	

(Table continued next page.)

Table 49. (Cont'd)

TRANSPORT			
Name	**Database**	**Specific dataset**	**Comment**
Truck	U.S. LCI	Transport, combination truck, diesel powered/US	
Train	U.S. LCI	Transport, train, diesel powered/US	
Boat, river	U.S. LCI	Transport, barge, average fuel mix/US	
Boat ocean	U.S. LCI	Transport, ocean freighter, average fuel mix/US	
Pipeline	EI	Transport, natural gas, pipeline, long distance/RER Transport, crude oil pipeline, onshore/RER	
END-OF-LIFE			
Name	**Database**	**Specific dataset**	**Comment**
Landfill of corrugated packaging	GaBi	US: Waste on landfill	Carbon modeled using methods described in Section 4.2.7.2
Incineration of corrugated packaging	GaBi	EU-27: Incineration of paper waste PE	Carbon modeled based on U.S. conditions

D. DETAILED INVENTORY DATA - AVERAGE CONTAINERBOARD

Table 50 presents the details of the containerboard data as collected.

Table 50. Detailed Containerboard LCI Data (per 1 odst of Containerboard)

Name	**Unit***	**Quantity**	**Average water content**
WATER INPUTS			
Water (process and cooling)	m^3	30.2	100%
FIBER INPUTS			
Logs, Northern Hardwood	odst	0.019	50.0%
Logs, Southern Hardwood	odst	0.082	50.0%
Logs, Northern Softwood	odst	0.035	50.0%
Logs, Southern Softwood	odst	0.505	50.0%
Chips, Northern Hardwood	odst	0.017	50.0%
Chips, Southern Hardwood	odst	0.030	50.0%
Chips, Northern Softwood	odst	0.062	50.0%
Chips, Southern Softwood	odst	0.193	50.0%
Recovered Paper, Mixed	odst	0.069	10.0%
Recovered Paper, Corrugated	odst	0.479	10.0%
Recovered Paper, Pulp Substitutes	odst	0.000	10.0%
Purchased BKMP	odst	0.000	10.0%
Purchased UBKMP	odst	0.000	10.0%
Purchased RNDI	odst	0.000	10.0%
CHEMICALS/ADDITIVES			
Aluminium sulfate	odst	1.23E-03	Total weight of water in chemicals: 1.05E-2 st
Caustic	odst	3.44E-03	
Starch	odst	4.94E-03	
Sulfuric acid	odst	6.14E-03	
Strength agents	odst	1.82E-03	
Lime	odst	1.60E-03	
Soda powder	odst	7.67E-03	
Dispersants	odst	6.73E-05	
Other fillers	odst	3.63E-03	
FUELS/ENERGY			
Purchased Hogged Fuel, Logging Residues	odst	8.16E-06	N/A
Purchased Hogged Fuel, Manufacturing Residues	odst	6.92E-05	N/A
Self-Generated Hogged Fuel, Logging Residues	odst	2.29E-06	N/A

(Table continued next page. See notes at end of table.)

Table 50. (Cont'd)

Name	**Unit***	**Quantity**	**Average water content**
FUELS/ENERGY			
Self-Gen Hydroelectricity	MMBtu	2.40E-03	N/A
Non-Recyclable Paper	tons	2.16E-06	N/A
Other biomass	tons	4.03E-06	N/A
Sludge	tons	2.70E-06	N/A
Coal	tons	6.19E-06	N/A
Distillate Fuel Oil (#2)	gal	1.06E-04	N/A
Gasoline	gal	0.00E+00	N/A
Kerosene	gal	0.00E+00	N/A
Liquid Propane Gas	gal	0.00E+00	N/A
Natural Gas	1000 ft3	5.20E00	N/A
Other Fuel	MMBtu HHV	6.37E-03	N/A
Residual Fuel Oil (#5,6)	gal	1.88E-01	N/A
Rubber Tire Chips	tons	3.60E-06	N/A
Purchased electricity	Million kWh	3.35E-04	N/A
Purchased steam	MMBtu	5.04E-01	N/A
PRODUCTS/COPRODUCTS			
Average containerboard	odst	1.00E00	8.2%
Turpentine and tall oil	odst	2.10E-02	N/A
Sold electricity	Million kWh	2.07E-05	N/A
EMISSIONS TO AIR			
Nitrogen oxides	st	1.17E-03	N/A
Sulfur oxides	st	5.37E-04	N/A
Total reduced sulfur	st	1.01E-04	N/A
Particulates	st	4.45E-04	N/A
Carbon monoxide	st	2.31E-04	N/A
Carbon dioxide, biogenic	st	0.917	N/A
Carbon dioxide, fossil	st	0.339	N/A
Methane, biogenic	st	2.66E-03	N/A
Methane, fossil	st	1.00E-05	N/A
Nitrous oxide	st	2.81E-05	N/A
Water evaporation	m^3	3.57	N/A
EMISSIONS TO WATER			
Process effluent	m^3	25.3	N/A
Cooling water discharges	m^3	2.13	N/A

(Table continued next page. See notes at end of table.)

Table 50. (Cont'd)

Name	**Unit***	**Quantity**	**Average water content**
EMISSIONS TO WATER			
Absorbable organic halides	st	1.61E-06	N/A
Biological oxygen demand	st	1.06E-03	N/A
Total suspended solids	st	1.08E-03	N/A
Total nitrogen	st	2.23E-04	N/A
Total phosphorus	st	3.37E-05	N/A
RESIDUALS			
Wastewater treatment plant residuals	odst	1.52E-02	N/Av.
Wood ashes	odst	1.29E-02	N/Av.
Coal ashes	odst	3.48E-04	N/Av.
Other solid wastes	odst	7.39E-02	N/Av.

**odst: oven dry short tons.*

E. MODIFIED MASS ALLOCATION

Mill-specific environmental release and energy consumption data for forest products manufacturing in the U.S. were available from surveys undertaken by the national industry organizations in the U.S. These data are aggregated at the whole mill level (e.g., total pounds of BOD_5 released in treated effluent from a mill in a year). Life cycle studies are often focused on particular consumer products. Because most mills make a variety of paper products, and sometimes from a variety of furnishes, use of mill-level environmental data in such studies calls for *allocation* of the mill environmental and energy burdens to the product(s) of interest made at the mills. ISO 14044 (ISO 2006b, 4.4.4.2, p. 14) addresses this issue:

> *"Wherever possible, allocation should be avoided by [...] dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes."*

This was applied as much as possible by collecting additional data (through a supplemental survey). However, this was not sufficient to fully resolve the need for allocation. In this case, ISO 14044 (ISO 2006b, 4.4.4.2, p. 14) specifies the following:

> *"Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e., they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system."*

To achieve this, the method outlined in Section 3.5.2.1 was applied, but again was not sufficient to completely solve the internal allocation problem.

One way to allocate environmental loads or energy consumption (hereafter referred to as "burdens") can be based on mass of product made. That is, if the product of interest accounts for half of the mass of all products manufactured at the mill, then half of the total mill burden would be allocated to that product. This method overlooks differences in burdens that might be contributed by different furnishes, however. For example, consider a mill that produces equal quantities of linerboard from 100% unbleached kraft pulp and corrugating medium from 100% OCC (recycled fiber). If the mill reported release of 100 tons of TRS, simple mass allocation would assign 50 tons of TRS to the kraft linerboard and 50 tons to the medium. However, process knowledge indicates that essentially all the TRS should be allocated to the linerboard because TRS releases from the kraft process, if present, will dwarf any releases from the OCC recycling process. Similarly, NCASI has detailed process knowledge related to environmental parameters and energy consumption that has been developed through decades of benchmarking studies of the data referenced above. In those studies, mills are categorized with more emphasis on their production processes than on their product types.

This appendix describes the modified mass allocation methodology that was used in this study. This methodology incorporates process knowledge to yield allocated environmental and energy burdens that better reflect the true burdens attributable to each product made at a mill.

E.1 Kraft Pulping Parameters

Some parameters are specific to kraft pulping: spent liquor, some air releases, and self-generated bark. These were allocated based on mass of kraft pulp produced.

E.2 Other Parameters

The proposed modified mass allocation methodology is summarized in this section using a hypothetical example mill for which the production information is provided in Table 51, with five separate production lines, which, according to industry survey data, made 787,100 short tons of finished products and released 1,442,464 pounds of BOD_5 in treated effluent.

Table 51. Example Mill Producing Multiple Products from Multiple Furnishes

Grade	Finished product	% of all products*
Corrugating medium	Recycled corrugating medium	17.8
Kraft paper	Bag and sack	4.4
Kraft paper	Bag and sack	11.1
Kraft paper	Wrapping paper	11.1
Linerboard	kraft linerboard	55.6

**Rounded to 1 decimal place. All available digits used in actual calculations.*

Table 52 shows the results of simple mass allocation of the BOD_5 burden for each finished product at the mill (by production line).

Table 52. Example Mill Simple Mass Allocation of BOD_5

Grade	Finished product	% of all products	BOD_5 simple mass allocation, lb*
Corrugating medium	Recycled corrugating medium	17.8	256,759
Kraft paper	Bag and sack	4.4	63,468
Kraft paper	Bag and sack	11.1	160,114
Kraft paper	Wrapping paper	11.1	160,114
Linerboard	kraft linerboard	55.6	802,010

**Rounded to the nearest integer.*

The total burden allocated to bag and sack production at this mill, using simple mass allocation, would be 223,582 lb., the total of the two bag and sack production lines.

Incorporation of process knowledge into the allocation calculation requires knowledge about (1) the production processes used at the mill, and (2) the burdens associated with those processes. Table 53 shows the furnish types, which are closely related to production processes, for each product, as derived from Fisher International information, for the example mill.

Table 53. Example Mill Products and Furnishes

Finished product	**% of all products**	**Furnish* as percent of total furnish for finished product**		
		RNDI	**SC**	**UBK**
Recycled corrugating medium	17.8	40	60	0
Bag and sack	4.4	8	0	92
Bag and sack	11.1	0	0	100
Wrapping paper	11.1	0	0	100
Kraft linerboard	55.6	6	0	94

** More details provided in Table 54.*

Table 54 lists NCASI benchmarking production categories, their descriptions, and the benchmarking production-weighted mean (PWM) loading rate for final effluent BOD_5 associated with each mapped production category. The mill count indicates the number of mills for which NCASI has information. These values can be updated each year. The latter information represents NCASI process knowledge that is incorporated into the allocations using the methodology presented here.

Table 54. NCASI Production Categories

NCASI production category	**Category description**	**Final effluent BOD PWM**	
		lb/ton*	**Mill count**
Bleached chemi-thermomechanical (BCTMP)	Mills that produce bleached chemi-thermomechanical market pulps.	**	**
Bleached kraft, integrated (BKI)	Mills that produce paper, market pulp, or bleached board whose total fiber is comprised of at least 75% bleached kraft pulp produced on-site, where market pulp represents less than 67% of total product.		
Bleached kraft, other (BKO)	Mills that produce bleached kraft or soda pulp comprising at least 18% but less than 75% of the fiber contained in final products. These mills make an assortment of final products that may incorporate mechanical pulps, secondary fiber, or purchased fiber.		
Bleached kraft (BK)	Combination of BKI and BKO	3	34
Bleached kraft market pulp (BKMP)	Mills that produce paper, market pulp, or bleached board whose total fiber is comprised of at least 75% bleached kraft pulp produced on-site, where market pulp represents at least 67% of total product.		
Bleached kraft dissolving (BKD)	Mills that produce dissolving grade bleached kraft pulps.		
Unbleached kraft 1 (UK1)	Mills whose final products are comprised of at least 85% unbleached kraft or semi-chemical pulps produced on-site. No pulp bleaching is done on-site.		

(Table continued next page. See notes at end of table.)

Table 54. (Cont'd)

NCASI production category	**Category description**	**Final effluent BOD PWM**	
		lb/ton*	**Mill count**
Unbleached kraft 2 (UK2)	Mills whose final products are comprised of less than 85% unbleached kraft or semi-chemical pulps produced on-site. The balance of the fiber furnish may include non-deinked secondary fiber, mechanical pulps. No pulp bleaching is done on-site.		
Unbleached kraft (UK)	UK1 and UK2 combined but excluding mills producing any bleached chemical pulp.	2	36
Semi-chemical (SC)	Mills producing corrugating medium from semi-chemical pulps produced on-site and non-deinked secondary fiber. They may also produce linerboard from recycled fiber.	0.7	7
Mechanical (MECH)	Mills whose final products are comprised primarily of mechanical pulps manufactured on-site. No chemical pulps are produced on-site.	0.5	2
Deinked tissue/fine papers (DTF)	Mills that produce tissue/toweling or fine papers from deinked secondary fiber produced on-site.		
Deinked newsprint (DNWS)	Mills that produce newsprint from deinked secondary fiber produced on-site.		
Recycled deinked newsprint and fine paper (RDI)	Combination of DTF and DNWS	0.7	9
Recycled tissue/fine papers (RTF)	Mills that produce tissue/toweling or fine papers from non-deinked secondary fiber produced on-site.		
Recycled containerboard (RCTR)	Mills that produce linerboard and corrugating medium, typically on fourdrinier machines, from non-deinked secondary fiber produced on-site.		
Recycled boxboard (RBOX)	Mills that produce boxboard, tube stock, and similar products, typically on cylinder machines, from non-deinked secondary fiber produced on-site.		
Recycled non-deinked (RNDI)	Combination of RTF, RCTR and RBOX	1	51
Non-integrated fine or lightweight papers (NIF)	Mills that produce fine or lightweight papers from purchased fiber.	2	2
Non-integrated other papers (NIO)	Mills that produce tissue, filter, or other papers from purchased fiber.		
Sulfite paper grade (SULF)	Mills that produce paper primarily from sulfite pulp produced on-site.	6	2
Sulfite dissolving pulp (SULD)	Mills that produce dissolving grade sulfite pulps.		

**Values rounded to one significant figure for illustration purposes. All available digits used in actual calculations.*
***There is no U.S. BCTMP production. North American PWM is 2 lb/st.*

The knowledge about the production processes used at the example mill and the PWM loading rates associated with those processes are combined with the simple mass allocation calculation in **Equation 1** to calculate the burden that would be associated with each product if the furnish production processes are contributing to the burden at their industry PWM rates:

$$B_i = P_{tot} P_i \sum_{j=1}^{f} F_{ij} M_{ij}$$ **Equation 1**

B_i: the expected burden associated with the ith product if all furnish processes are contributing at their industry PWM rates

P_{tot}: the total production for all products at the mill

P_i: the fraction of total production represented by the ith product

F_{ij}: the fraction of the total furnish for the ith product represented by the jth furnish

M_{ij}: the industry PWM loading rate for the jth furnish of the ith product

f: the number of furnishes for the ith product.

For example, the expected annual load of BOD_5 associated with recycled corrugating medium at the example mill is:

$$B_{\mathrm{Re}cyCM} = 787{,}100\,tons\,(0.178)\left[0.40(1\,lb/ton) + 0.60(0.7\,lb/ton)\right] = 114{,}885\,lb$$

The fractional allocation of the whole mill burden to the ith product is computed using **Equation 2**:

$$A_i = \frac{B_i}{\sum_{i=1}^{p} B_i}$$ **Equation 2**

A_i: the fractional allocation of whole mill burden to the ith product
p: the number of products made at the mill

Table 55 presents the results from Equations 1 and 2 for the example mill.

Table 55. Example Mill BOD_5 Allocations Incorporating Process Knowledge

Finished product	P_i, %	$P_{tot}P_iF_{ij}M_{ij}$, lb			Equation 1	Equation 2
		NDI	SC	UK	B_i*, lb	A_i, %
Recycled corrugating medium	17.8	56,042	58,844	0	114,885	8.3
Bag and sack	4.4	2,771	0	63,724	66,494	4.8
Bag and sack	11.1	0	0	174,736	174,736	12.7
Wrapping paper	11.1	0	0	174,736	174,736	12.7
kraft linerboard	55.6	26,258	0	822,740	848,998	61.5
Totals*	**100**	**153**	**38.3**	**165**	**1,379,849****	**100**

**Totals shown may differ from the sum of components due to rounding. In the actual calculations, only the final result is rounded. **The expected average total load for a mill like the example mill is about 1.38 million lb BOD_5, which is slightly less than the 1.44 million lbs. the mill reported releasing. This indicates that release rates for one or more production processes at the mill are slightly greater than the industry production weighted mean loading rates for those processes. See the Limitations section for a discussion of the implications of this kind of discrepancy.*

For ease of implementation in spreadsheets and database queries, the calculations can be simplified by substituting Equation 1 for B_i in Equation 2:

$$A_i = \frac{P_{tot} P_i \sum_{j=1}^{f} F_{ij} M_{ij}}{P_{tot} \sum_{i=1}^{p} \left(P_i \sum_{j=1}^{f} F_{ij} M_{ij} \right)} \quad \textbf{Equation 3}$$

Equation 3 can then be reduced to **Equation 4**:

$$A_i = \frac{P_i \sum_{j=1}^{f} F_{ij} M_{ij}}{\sum_{i=1}^{p} \left(P_i \sum_{j=1}^{f} F_{ij} M_{ij} \right)} \quad \textbf{Equation 4}$$

If Equation 4 is used for the calculation it is not necessary to know the total production at the mill. While Equation 2 is, perhaps, easier to grasp conceptually, Equation 4 may be easier to implement in a spreadsheet or in database queries.

With values for A_i for each product, actual burdens allocated to each product can be calculated by multiplication of A_i and the total reported burden for the mill. Results for the example mill are shown in Table 56.

Table 56. Example Mill Mass Allocation of BOD_5 with and without Incorporation of Process Knowledge

Finished product	**Simple allocation based on product mass**		**Allocation incorporating process knowledge**		
	% of all products	**BOD_5, lb**	**A_i, %**	**BOD_5, lb**	**Difference from simple allocation, lb**
Recycled corrugating medium	17.8	256,759	**8.3**	**120,098**	**-136,661**
Bag and sack	4.4	63,468	**4.8**	**69,512**	**6,044**
Bag and sack	11.1	160,114	**12.7**	**182,665**	**22,551**
Wrapping paper	11.1	160,114	**12.7**	**182,665**	**22,551**
kraft linerboard	55.6	802,010	**61.5**	**887,523**	**85,513**
Totals*	100	1,442,464	**100**	**1,442,464**	**0**

**Totals shown may differ from the sum of components due to rounding. In the actual calculations, only the final result is rounded.*

Compared to simple product mass allocation, the allocations calculated from Equation 2 (or 4) shift over half of the load from the recycled corrugating medium, which contains no kraft pulp produced on-site, to the other products, which are made primarily from kraft pulp. The shift occurs because the PWM loading rate for kraft furnish (3 lb/t) is higher than the PWMs for the recycled (1 lb/t) and semichemical (0.7 lb/t) furnishes for the corrugating medium.

For burdens that are dependent on the fuel type and/or combustion conditions for heat and power generation at a mill (e.g., greenhouse gases, power boiler sulfur dioxide, and nitrogen oxides), the fractional allocated burdens are the same as the fractional allocation for energy consumption associated with generation of those burdens. For example, only the fossil energy allocation would be used to allocate greenhouse gas releases. For allocation of energy consumption, the calculations are done exactly as illustrated here using production-weighted mean energy consumption rates that are related to the furnish production processes. Individual fuel allocations are done using allocations for the appropriate kind of energy. For example, fossil fuel consumption is allocated using the allocation fraction computed for fossil energy consumption. Biofuel consumption is allocated using the bioenergy allocation fraction. Purchased electricity is allocated separately given that this energy source is also related to production type, particularly for mechanical pulping.

The proposed methodology is based on knowledge of the production-weighted mean environmental loading and energy consumption rates associated with particular production processes (i.e., furnishes). For any parameter for which a relationship with particular production processes can be credibly established, the methodology should yield reasonably accurate allocations.

To the extent that the relationship between loadings and furnish processes at a particular mill differ from the PWMs, the allocations will be inaccurate. As noted above, it is apparent that BOD_5 release rates for one or more production processes at the example mill are slightly greater than the industry PWMs for those processes. If all processes at the mill are similarly elevated, perhaps because the wastewater treatment plant is unusually inefficient, then the allocations should be reasonably accurate. If, however, only some processes are elevated, perhaps because of unusually poor black liquor spill control causing just the UK releases to be elevated, error would be introduced into the allocations for an individual mill. Of course, if the latter situation could be accurately identified at all mills, there would be little need for allocation methodologies like those proposed here. The effect of this kind of inaccuracy should diminish as allocated loads from a number of mills are combined to produce production-weighted mean allocated burdens for further use in a life cycle study.

F. NUMBER OF USES METHOD

F.1 Introduction

The ISO 14044 Standard (ISO 2006b) recommends, where allocation for open-loop recycling cannot be avoided through system expansion or by using a closed-loop approximation, that “the allocation procedures for the shared unit processes … should use, as the basis for allocation, if feasible, the following order:

- Physical properties (e.g., mass);
- Economic value (e.g., market value of the scrap material or recycled material in relation to market value of primary material); or
- The number of subsequent uses of the recycled material (see ISO/TR 14049).”

The Number of Uses (NOU) Method, as described in the ISO/TR 14049 Technical Report (ISO 2012b), was used as an alternative approach when comparing the 100%-recycled and industry-average products. This allocation procedure is based on physical properties and number of subsequent uses of the recovered material. The steps, as described by the ISO/TR 14049 Technical Report, are presented in Figure 50.

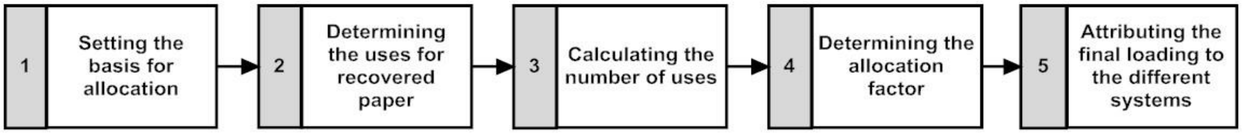


Figure 50. Stepwise Procedure for Applying the Number-of-Uses Allocation Procedure to Pulp and Paper Products

F.2 Application of the NOU Method to Corrugated Product

This section discusses the determination of which proportion of the environmental burden associated with the production of industry-average corrugated product from fresh fiber stays within the studied system and which portion is transferred to subsequent uses.

F.2.1 Recovery of OCC

<u>Setting the Basis for Allocation</u>

The “basis” upon which the allocation factor is made – that is, the total loading that will be allocated between the primary product and the products derived from recycled fibers – reflects the loadings associated with the primary product system, through the end of product life.

<u>Determining the Uses for Recovered Paper</u>

According to AF&PA, the average recovery rate of OCC in 2014 was 89.5%. The NOU Method was applied only to the fraction considered to be in closed-loop[25] applicable only to open-loop

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[25] The true application of the NOU Method would be to apply a credit for everything that is recycled and import burden to all use of recovered fiber, which is the same as applying it to the closed-loop fraction only.

recycling which represents 47.0% (the other 42.5% being recycled in closed-loop). As illustrated in Figure 51, OCC is recovered, when not used for containerboard production, into tissue paper, packaging paper, paperboard (including construction paper and board), P&W paper products, and newsprint (exports are not considered in this figure) (AF&PA 2009)[26]. Parameters for calculating the number of uses are presented in Table 57. To simplify the calculation procedure, the closed-loop assumption was made for the second and higher passes of recycling (i.e., $z_3 = x_3$), as proposed in ISO 14049.

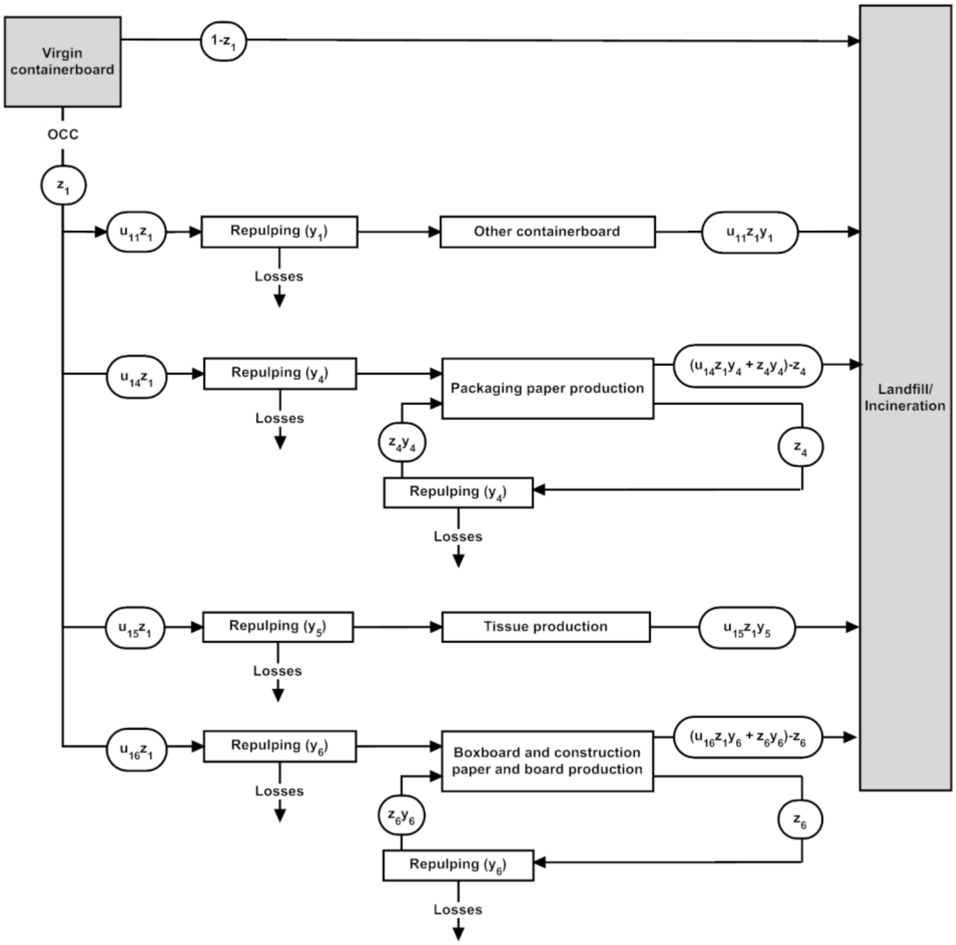

Figure 51. Uses of Recovered OCC: Open-Loop Recycling

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[26] NCASI NOU model is based on 2008 industry data. The model has not been updated since that time, but this is not expected to have significant effect on the number of uses calculated.

Table 57. Data for Calculating the Number of Uses of OCC

z_1	$0.47^§$				
u_{11}*,§	0	**y1†**	0.95	**z1‡**	0.892
u_{14}*	0.136	**y4†**	0.90	**z4‡**	0.277
u_{15}*	0.057	**y5**	0.65		
u_{16}*	0.807	**y6†**	0.90	**z6‡**	0.770

**u_{ij} from AF&PA (2015) † y_i from Clark et al. (1987). ‡z_i from U.S. EPA (2015), for each grade the most recent available data was used. §When applying the number of use to the industry-average, only the fraction in open-loop recycling was considered. In consequence, OCC recovered in containerboard was not considered.*

Calculating the Number of Uses

In the system illustrated in Figure 51, the number of uses can be calculated as follows:

$$u \approx 1 + z_1[u_{14}y_4/(1-z_4y_4) + u_{15}y_5 + u_{16}y_6/(1-z_6y_6)] \approx 2.22$$

Determining the Allocation Factor and Attributing the Final Loading to the Different Systems

The allocation factor for fresh fiber production can be calculated as follows:

$$A_v = (1- z_1) + (z_1/u) = 0.74$$

This means that 74% of the environmental burden from using fresh fiber for production of containerboard stays within the system and 26% is exported to subsequent uses.

The environmental impacts were calculated as an industry-average that consists of a mix of fresh fiber and recycled pulp production. At this level, the data did not allow determination of which fraction of the environmental impacts arising at pulp and paper mills is attributable to the fresh fiber production, and thus to apply the calculated allocation factor directly. The following procedure was used as an approximation.

- In cases where it is obvious that an environmental burden is attributable to fresh fiber production (e.g., direct consumption of wood fiber, purchased fresh fiber pulp, etc.), the allocation factor A_v was applied directly.
- For other cases, the fraction of product manufactured from fresh fiber (f_v) was determined based on the inputs of recovered paper, wood, and purchased pulp, and using typical yields.
- The calculated fraction was used to calculate a corrected allocation factor, which was further adjusted with a variable factor F in the case of effluent, water use, and energy to account for typical differences in fresh fiber and recycled production ($A_v' = A_v f_v F$).
- The corrected allocation factor (A_v') was applied to environmental impacts.

F.2.2 Use of Recovered Paper to Produce Industry-Average and 100%-Recycled Products

It was also necessary to calculate the fresh fiber production burden that comes with consumption of recovered paper for production of containerboard (industry-average and 100%-recycled) products. Mixed papers and pulp substitutes (PS) were also recovered into containerboard. An allocation factor needed to be calculated for these three. A similar approach to the one described above, but where the fraction of fresh fiber load attached with a given amount of recovered fiber is calculated instead, was applied. More details regarding the applied approach can be found elsewhere (NCASI 2012). The calculated allocation factors were as follows:

- mixed papers: 0.18 kg of fresh fiber production/kg of recovered mixed paper; and
- pulp substitute: 0.25 kg of fresh fiber production/kg of recovered PS.

In the case of the 100%-recycled product, no fresh fiber production burden is exported, but a fresh fiber production burden is imported for each ton of recovered fiber used, including OCC. That allocation factor was estimated with the method described above: 0.15 kg of fresh fiber production burden/kg of additional OCC.

The fresh fiber production burden associated with each of the recovered fiber grade were approximated as follows:

- mixed papers: bleached kraft market pulp modeled using AF&PA data (NCASI 2010);
- pulp substitute: all other linerboard as modeled in this study; and
- OCC: all other linerboard as modeled in this study.

G. IMPACT INDICATORS

G.1 Global Warming (GW)

The mechanism of the greenhouse effect can be observed on a small scale, as the name suggests, in a greenhouse. These effects are also occurring on a global scale. The short-wave radiation from the sun comes into contact with the earth's surface and is partly absorbed (leading to direct warming) and partly reflected as infrared radiation. The reflected part is absorbed by so-called greenhouse gases in the troposphere and is re-radiated in all directions, including back to Earth. This results in a warming effect at the earth's surface. In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. Greenhouse gases that are considered to be caused, or increased, anthropogenically are, for example, carbon dioxide, methane, and CFCs. Figure 52 shows the main processes of the anthropogenic greenhouse effect. An analysis of the greenhouse effect should consider the possible long-term global effects. The global warming potential is calculated in carbon dioxide equivalents (CO_2 eq.). This means that the greenhouse potential of an emission is given in relation to CO_2. Given that the residence time of the gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A period of 100 years is customary.

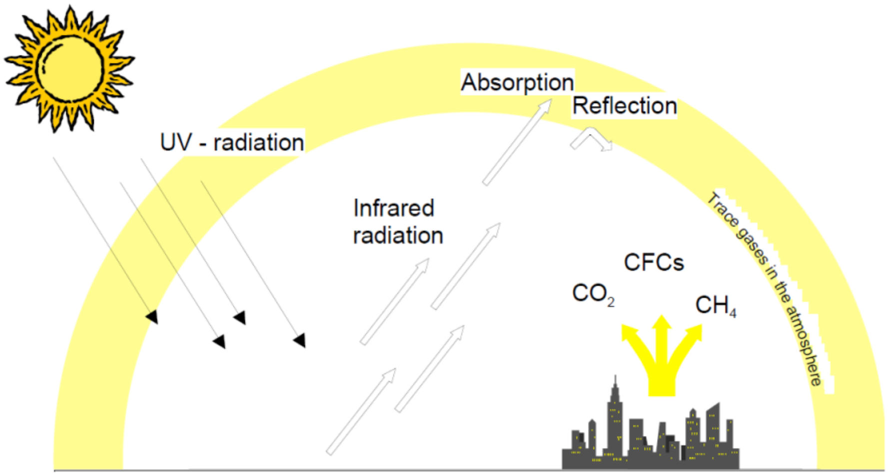

Figure 52. Greenhouse Effect

G.2 Ozone Depletion (ODP)

Text taken from Bare et al. (2003, p. 56)

Ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances. Recent anthropogenic emissions of chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances are believed to be causing an acceleration of destructive chemical reactions, resulting in lower ozone levels and ozone "holes" in certain locations. These reductions in the level of ozone in the stratosphere lead to increasing ultraviolet-B (UVB) radiation reaching the earth. As shown in Figure 53, increasing UVB radiation can cause additional cases of skin cancer and cataracts. UVB radiation can also have deleterious effects on crops, materials, and marine life. International consensus exists on the use of ozone depletion potentials, a metric proposed by the World Meteorological Organization for calculating the relative importance of CFCs, hydrochlorofluorocarbons (HFCs), and halons expected to contribute significantly to the breakdown of the ozone layer. The reference substance is CFC-11 (CFC-11 eq.).

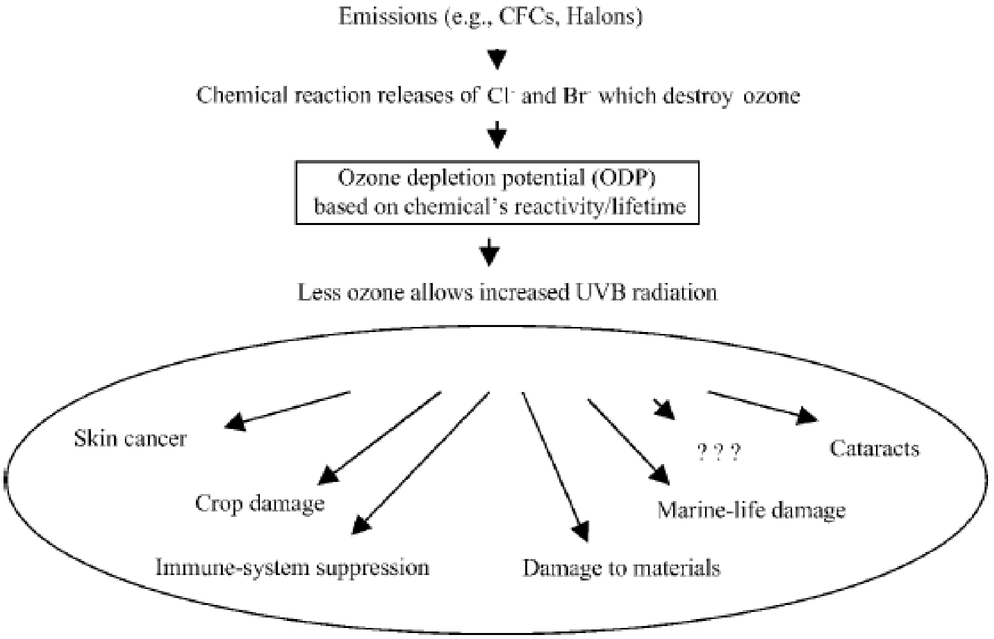

Figure 53. Ozone Depletion Impact Pathways
[Figure taken from Bare et al. (2003, p. 54)]

G.3 Acidification (AP)

The acidification of soil and water occurs predominantly through transformation of air pollutants into acids. This leads to a decrease in the pH value of rainwater and fog from 5.6 to 4 and below. Sulfur dioxide, nitrogen oxide, and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions. This damages ecosystems, whereby forest dieback is the most well-known impact. Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and natural stones that are corroded or disintegrated at an increased rate. When analyzing acidification, it should be considered that although it is a global problem, the regional effects of acidification could vary. Figure 54 displays the primary impact pathways of acidification. The acidification potential is given in sulfur dioxide equivalents (SO_2 eq.). The acidification potential is described as the ability of certain substances to build and release H+ - ions. Certain emissions can also be considered to have an acidification potential, if the given S-, N- and halogen atoms are set in proportion to the molecular mass of the emission. The reference substance is sulfur dioxide.

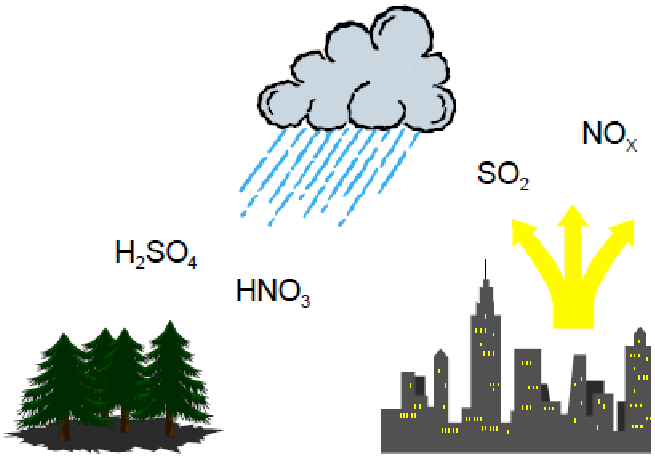

Figure 54. Acidification Impact Pathways

G.4 Eutrophication (EP)

Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilization in agriculture all contribute to eutrophication. The result in water is accelerated algae growth, which in turn prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. In addition, oxygen is needed for decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulfide and methane are thereby produced. On eutrophicated soils, increased susceptibility of plants to diseases and pests is often observed, as is degradation of plant stability. If the eutrophication level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater. Nitrate also can end up in drinking water. Nitrate at low levels is harmless from a toxicological point of view. However, nitrite, a reaction product of nitrate, can be toxic to humans at excessive doses. The causes of eutrophication are displayed in Figure 55.

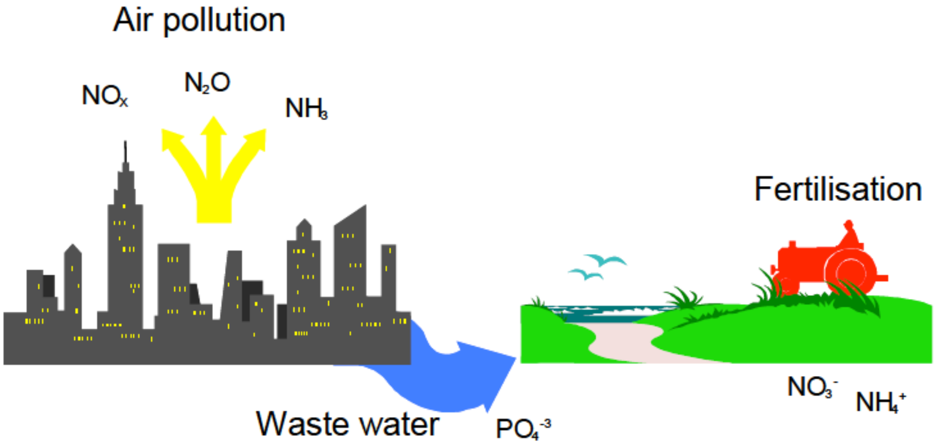

Figure 55. Eutrophication Impact Pathways

The eutrophication potential is calculated in nitrate equivalents (N eq.). As with acidification potential, it's important to remember that the effects of eutrophication potential differ regionally and can vary significantly in different water bodies.

G.5 Photo-Chemical Oxidant Formation (Smog, POCP)

Despite playing a protective role in the stratosphere, at ground-level ozone is classified as a damaging trace gas. Photo-chemical ozone production in the troposphere, also known as summer smog, is suspected of damaging vegetation and material. High concentrations of ozone are toxic to humans. Radiation from the sun in the presence of nitrogen oxides and hydrocarbons can result in complex chemical reactions, producing aggressive reaction products, one of which is ozone. Nitrogen oxides alone do not cause high ozone concentration levels. Hydrocarbon emissions occur from incomplete combustion, in conjunction with petrol (storage, turnover, refueling etc.) or from solvents. High concentrations of ozone arise when the temperature is high, humidity is low, when air is relatively static, and when there are high concentrations of hydrocarbons. Because CO (mostly emitted from vehicles) reduces the accumulated ozone to CO_2 and O_2, high concentrations of ozone do not often occur near hydrocarbon emission sources. Higher ozone concentrations more commonly arise in areas of clean air, such as forests, where there is less CO (Figure 34). In TRACI, photo-chemical ozone formation is referred to in ozone equivalents (O_3 eq.). When analyzing, itit is's important to remember that the actual ozone concentration is strongly influenced by the weather and by the characteristics of the local conditions.

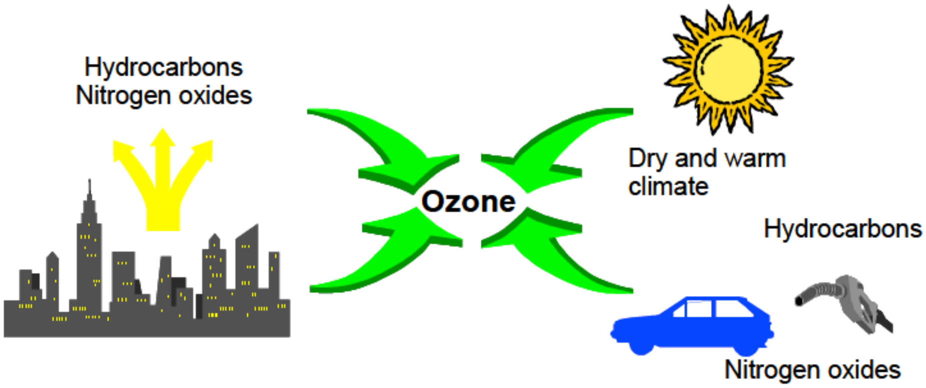

Figure 56. Photo-Chemical Oxidant Formation Impact Pathways

G.6 Respiratory Effects (Particulates, RES)

Text taken from Bare et al. (2003, p. 66).

Ambient concentrations of particulate matter (PM) are strongly associated with changes in background rates of chronic and acute respiratory symptoms, as well as mortality rates. Ambient particulate concentrations are elevated by emissions of primary particulates, measured variously as total suspended particulates, PM less than 10 µm in diameter (PM10), PM less than 2.5 µm in diameter (PM2.5), and by emissions of SO_2 and NO_x, which lead to the formation of the so-called secondary particulates sulfate and nitrate. In TRACI, respiratory effects are computed as PM2.5 equivalents (PM2.5 eq.).

G.7 Abiotic Resource Depletion, Fossil Fuel (FF, NRPE)

Several ways of analyzing fossil fuel and energy consumption exist (Bare et al. 2003). Many of these techniques acknowledge a preference for renewable energy sources as opposed to non-renewable energy sources.

GaBi proposes a non-renewable **Primary Energy Demand** (NRPE) indicator. Primary Energy Demand is often difficult to determine due to the various types of energy sources. Primary Energy Demand is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere, or energy source without any anthropogenic change. For fossil fuels and uranium, this would be the amount of resource withdrawn expressed in its energy equivalent (i.e., the energy content of the raw material). For renewable resources, the energy-characterized amount of biomass consumed would be described. For hydropower, it would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e., from the height difference). The total “primary energy consumption non-renewable,” given in MJ, essentially characterizes the gain from the energy sources natural gas, crude oil, lignite, coal, and uranium. Natural gas and crude oil are used both for energy production and as material constituents (e.g., in plastics). Coal is primarily used for energy production. Uranium is only used for electricity production in nuclear power stations.

TRACI (Bare et al. 2003, p. 68) argues that, although a useful measure, primary energy demand does not fully address potential depletion issues associated with energy consumption. For example, solid and liquid fuels are not perfect substitutes (i.e., solid fuels are not currently practical in personal transportation applications). For this reason, depletion of petroleum has different implications than depletion of coal, and so forth. TRACI quantifies **Fossil Fuel Depletion** (FF) by taking into account the fact that continued extraction and production of fossil fuels tends to consume the most economically recoverable reserves first, so that (assuming fixed technology) continued extraction will become more energy-intensive in the future. This is especially true once economically recoverable reserves of conventional petroleum and natural gas are consumed, leading to the need to use non-conventional fuels such as oil shale.

G.8 Renewable Primary Energy Demand (RPE)

GaBi proposes a renewable Primary Energy Demand indicator. Primary Energy Demand is often difficult to determine due to the various types of energy sources. Primary Energy Demand is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere, or energy source without any anthropogenic change. For fossil fuels and uranium, this would be the amount of resource withdrawn expressed in its energy equivalent (i.e., the energy content of the raw material). For renewable resources, the energy-characterized amount of biomass consumed would be described. For hydropower, it would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e., from the height difference). The total “primary energy consumption renewable,” given in MJ, is generally accounted separately and comprises hydropower, wind power, solar energy, and biomass. Feedstock energy, that is the energy of raw material inputs that are not used as an energy source to a product system (e.g., wood into pulp), was not included.

G.9 Water Use and Consumption (WU, WC)

In this study, water use is defined as the water withdrawn from the environment. This is referred to as "water withdrawal" in ISO 14046 (ISO 2014). Turbine water was not included in water use. Water consumption is that portion of water withdrawn from a source that is not directly returned after use or consistent with ISO14046 (ISO 2014, p. 3) *"water removed from, but not returned to, the same drainage basin [either] because of evaporation, transpiration, integration into a product, or release into a different drainage basin or the sea".* It is the water that is no longer available because it has been evaporated, transpired, incorporated into products, or otherwise removed from the water environment. In this report, evapotranspiration is not accounted within water consumption and water use for forest growth is not accounted within water use. Figure 57 presents the connection of the forest products industry to the water cycle.

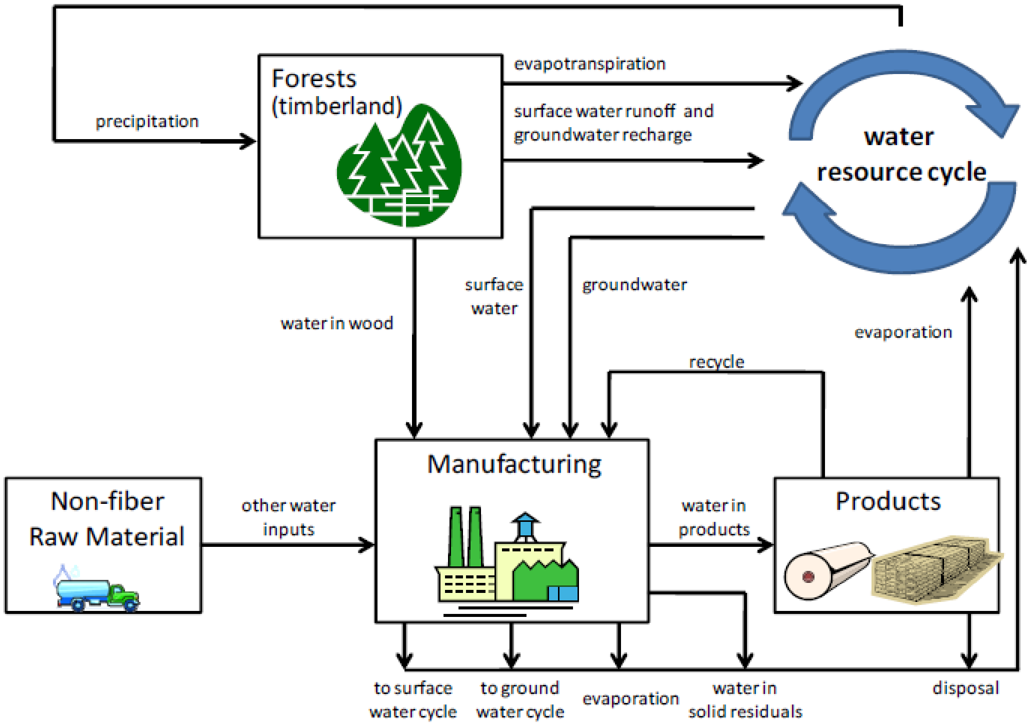

Figure 57. Connection of the Forest Products Industry to the Water Cycle

G.10 Human Toxicity (Tox) and Ecotoxicity (ECO)

Toxicity and ecotoxicity indicators attempt to quantify impacts on human health and ecosystems due to emissions of toxic substances. TRACI models impacts to human health and ecosystems based on the USEtox™ methodology (Rosenbaum et al. 2008). USEtox™ is a model based on scientific consensus for characterizing human and ecotoxicological impacts of chemicals in life-cycle impact assessment. The main output includes a database of recommended and interim characterization factors including environmental fate, exposure, and effect parameters for human toxicity and ecotoxicity. According to Rosenbaum et al. (2008), contributions of 1%, 5% or 90% to the total toxicity score are essentially equal but significantly larger than those of a chemical contributing to less than one per thousand or less than one per million of the total score. In practice, this means that for LCA practitioners, these toxicity factors are useful to identify the ten or twenty most important toxic substances pertinent for their applications. Once these most important substances have been identified, further analysis can be carried out on the life cycle phase, application components responsible for these emissions, and the respective importance of fate, exposure, and effect in determining the impacts of this chemical.

H. TOXICITY INDICATOR RESULTS

According to Rosenbaum et al. (2008), contributions of 1%, 5%, or 90% to the toxicity score are essentially equal but significantly larger than those of a chemical contributing to less than one per thousand or less than one per million of the total score. For this reason, they recommend that the USEtox method be used to identify the ten or twenty most important toxic substances pertinent for their applications. Once these most important substances have been identified, further analysis can be carried out in the life cycle phase, application components responsible for these emissions, and the respective importance of fate, exposure, and effect in determining the impacts of this chemical.

In this section, the substance contributing to more than 1% to toxicity categories, as well as their sources, are documented in no specific order. Table 58 presents the substances that contribute to more than 1% of the human health non-cancer impact category, Table 59 the substances that contribute to more than 1% of the human health cancer impact category, and Table 60 the substances that contribute to more than 1% of the ecotoxicity impact category.

Table 58. Contributors to the Human Health Non-Cancer Impact Category (HHNC)

Substance	**Unit processes contributors**
Lead to soil	Electricity generation
Mercury to soil	Electricity generation
Zinc to soil	Land application of ashes and WWTP residuals, electricity generation

Table 59. Contributors to the Human Health Cancer Impact Category (HHC)

Substance	**Unit processes contributors**
Mercury to air	Spent liquor combustion at P&P mills and electricity facilities
Arsenic to soil	Electricity generation
Lead to soil	Electricity generation
Mercury to soil	Electricity generation

Table 60. Contributors to the Ecotoxicity (ECO) Impact Category

Substance	**Unit processes contributors**
Cadmium to water	Natural gas production
Copper to water	Natural gas production
Silver to water	Natural gas production
Zinc to water	WWTP sludge landfilling

I. DETAILED PEER REVIEW COMMENTS AND ANSWERS

The next pages present the detailed critical review comments and how they were resolved.

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
1	LB	14			te	It reads: This study was performed following the principles described in the ISO 14040/14044 standards for a publicly disclosed study. "Requirements" are missing. Consider revising it: e.g., The study follows the principles described in the ISO 14040 Standard (ISO 2006a) and has been conducted according to the requirements of the ISO 14044 Standard (ISO 2006b)	Update accordingly	Done	Closed
2	LB	16		Figure 1	te	1. Revise the title - see the underlined text System Boundary for the Corrugated Product System 2. Why are the Figure 1 data not identical with Figure 11 data? It is supposed to be the same Figure. Which Figure is correct? 3. Figure 1 0.62 kg (0.52+0.10) recovered fiber/1.10 CBD or 1 kg CP Figure 11 0.57 kg (0.48+0.09) recovered fiber//1.10 CBD or 1 kg CP Table 15 0.60 kg recovered fiber/1.09 CBD or 1 kg CP Table 43 0.60 kg recovered fiber/ 1 kg CP. Table 44 0.613 kg recovered fiber per 1.09 CBD or 1kg CP Which factors are the correct ones? Update the Figures/Tables/Text thoroughly to match the data in the LCA report.	Update accordingly	1. Done, 2. Figure 11 was the wrong one. Changed to be the same as Figure 1. 3. Figure is correct. Text was corrected. Some of the errors was because We were reporting the numbers prior to them being corrected for mass/carbon balance.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
3	LB	18			te	Page 18, It reads: Impacts on land use and biodiversity <u>were not</u> quantified as there is no consensus method suitable for forest management. Page 90 reads: <u>It was assumed that there was no change in forest carbon stocks attributable to wood harvested to make containerboard.</u> In other words, the greenhouse gas emissions from land-use change are assumed null. This is in line with ISO 21930:2017 , 7.2.11 Greenhouse gas emissions from land-use change " Revise the statement on page 18 to be aligned with page 90. <u>09/11/23</u> Based on the statement on page 90, I suggest the following modification of the sentence on page 18 below: <u>Except for the greenhouse gas emissions from land-use change</u>, impacts on land use and biodiversity were not quantified as there is no consensus method suitable for forest management.	Update accordingly	Statement on p. 18 relates to biodiversity and that of p. 90 to carbon. No revision made.	Closed
4	LB	18			te	It reads: ...non-renewable primary energy demand and renewable primary energy demand. Specify "HHVs" are used. ...non-renewable primary energy demand and renewable primary energy demand<u>, HHVs.</u>	Update accordingly	Done	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
5	LB	15-18	TS3. The Study Design and Methods Employed		te	The Technical summary should provide a few paragraphs on the industry average plant samples representativenes. What strategy (ies) did the CPA apply to determine representative industry average plant samples for this LCA? For E.g. it should address the following aspects, • Sample size- The sample size should be identified per industry, for example, at least X facilities per member company. Are all member companies included in this LCA? Yes/ No, and why not? • Reference year- unusual/untypical production years shall be avoided, e.g., 2020, COVID-19, Disruption of the production and upstream suppliers. Provide a note of why 2020 was selected as a reference year. e.g., it was business as usual for this industry? Conservative choice despite the disruption. • Technological representativeness – a mix of applicable technologies significantly dominating the NA market, including old, average, and modern technologies. Is this the case? Yes/ No, and why not? • Production scale- a mix of small, medium, and large operations. Is this the case? Yes/ No, and why not? • Geographical representativeness – a mix of Eastern, Western and Central facilities - Yes/ No and why not. • Percentage of all the plants that took part in 2020 LCA. Add in the TS. "The study was based on information from 51 containerboard mills representing 69% of 2020 U.S. containerboard production and 402 converting facilities representing 57% of overall containerboard converting production volume for 2020". This item should also be addressed under "limitations and recommendations for future LCA iterations- see ISO 14040_44 Reqs	Update accordingly	There was no sample size. Questionnaires were sent to all members of AF&PA/NCASI/FBA and everyone that supplied data was included. This is the same approach that was used in the past. LCA was updated every 4 years starting in 2006 and industry decided not to update in 2018. 2020 was selected because the 2014 LCA was getting old, because industry assembles data every even years.Despite Covid, 2020 was a normal production year for containerboard mills and converting. The sample size is judged sufficient to represent the industry.We added one paragraph in the TS.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
6	LB	23		Table 2	te	Table 2- 2020, 0.51 kg/kg CBD- OCC to other users. This factor does not match the Figure 11 data- 0.62 kg/kg CP-- OCC to other users. Which factor is correct?	Update accordingly	Corrected	Closed
7	LB	27		Table 3	te	Table 3-2020, 0.52 kg/kg CBD -OCC to other users? Table 2- 2020, 0.51 kg/kg CBD- OCC to other users? Figure 11 - 0.62 kg/kg CP- OCC to other users? Which factor is correct?	Update accordingly	Corrected.	Closed
8	LB	27		Table 3	ge	Total biomass fuels Units are missing (kg?). Update accordingly.	Update accordingly	Added.	Closed
9	LB	28		Figure 6	te	Similar to Figure 7, Figure 6 should include GW, Excl BioCO2. It is missing	Update accordingly	Added.	Closed
10	LB	29		Figure 7	te	It reads: On the other hand, the difference is not significant when applying the stock change accounting method or when ignoring the emissions of biogenic CO2. Suggest adding a disclaimer here: "It should be noted that greenhouse gas emissions from land-use change are assumed null (see ISO 21930:2017 , 7.2.11Greenhouse gas emissions from land-use change ". *Wood from sustainably managed forests may be accounted for as having zero emissions concerning land-use change. This includes wood products responsibly sourced and certified to the Canadian Standards Association (CSA), Forest Stewardship Council (FSC) and Sustainable Forestry initiative (SFI)* *Standards, as well as all other standards globally endorsed by the Programme for the Endorsement of Forest Certification International (PEFC International) and the FSC*	Update accordingly	Updated	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
11	LB			Table 7	ge	Containerboard plants- do NOT add up. Converting plants- do add up. Add a clarification note in that regard explaining why so that it does not seem like an error.	Update accordingly	Added.	Closed
12	LB			Figure 9/3.3	te	Provide a clarification note that CBD plants (total of 77) are mostly located on the East Coast, so it does not look like an unbalanced/skewed industry average plant sample with an overrepresentation of the Eastern versus Western and Central facilities. Provided a breakdown of CBD by US region in 2020 (total of 77), Eastern- e.g., 80% Western-e.g., 10% Central- e.g., 10% Based on this info, sensitivity analysis should be conducted to check the impact of the electricity grid on the 2020 Industry Average CP- see ISO 14044- TE30 comment.	Update accordingly	Added.	Closed
13	LB			Figure 10/3.3	te	Similar comment, Provide a clarification note that converters (total of 1153) are mostly located on the East Coast, so it does not look like an unbalanced/skewed industry average plant sample with an overrepresentation of the Eastern versus Western and Central facilities. Provided a breakdown of converters by US region in 2020 (total of 1153), Eastern- e.g., 90% Western-e.g., 5% Central- e.g., 5% Based on this info, sensitivity analysis should be conducted to check the impact of the electricity grid on the 2020 Industry Average CP- see ISO 14044- TE30 comment.	Update accordingly	Added.	Closed
14	LB			Figure 11	te	Figure 11 and Figure 1 should be identical. Which Figure is correct?	Update accordingly	Corrected.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
15	LB			3.5.2	te	It reads: The data available in the U.S. LCI database for sawmill co-products were developed by CORRIM (Kline 2004, Milota 2004, Milota et al. 2004, Wilson and Sakimoto 2004) using mass allocation. You should add a clarification note that mass allocation is a "Conservative" allocation parameter for the corrugated products.	Update accordingly	Added.	Closed
16	LB	44		footnote 6	te	Note that ISO 21930:2017, provides the following definitions. **3.4.6** **co-product** any of one or more products (ISO 14050:2009, 3.2) from the same unit process (3.4.1), but which is not the object of the assessment Note 1 to entry: Co-product and product have the same status and are used for identification of several distinguishable flows of products from the same unit process. Where one of two or more co-products is the object of assessment of the EPD (3.1.1), this is normally considered the product and the other output(s) (ISO 14040:2006, 3.25) as the co-product(s). Where one of the co-products is an input (ISO 14040:2006, 3.21) to a process (ISO 14040:2006, 3.11), this is normally considered as a product input. From co-product and product, waste (3.3.11) is the only output to be distinguished as a non-product. [SOURCE: ISO 14040:2006, 3.10, modified — The definition has been clarified relative to the object of assessment and Note 1 to entry has been added.] **3.4.7** **by-product** co-product (3.4.6) from a process (ISO 14040:2006, 3.11) that is incidental or not intentionally produced and which cannot be avoided Note 1 to entry: Wastes (3.3.11) are not by-products.	Update accordingly	Note sure what you are suggesting here as modification but we simply deleted the footpnote.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
17	LB	48			te	It reads: This method is not specifically mentioned in the ISO 14044 Standard or its accompanying ISO 14049 Technical Report. This statement is NOT quite true. See Figures 15 and 17, ISO 14079 case study. Figure 12, LCA is a similar adaptation of ISO 14079, case study. 09/11/23. Understood. item closed	Update accordingly	Statement is about cut-off. We did not apply the closed-loop recycling as described in Figure 15 which would involve adjusting the production of virgin/recycled material to match the recovery rate. Closed-loop approximation just refers to the fact that we did not consider OCC might have been imported.	Closed
18	LB	48			te	It reads: However, the ISO Standard is not stringent regarding which allocation method should be applied. ISO 14044/Amd:2 2020 provided additional information to best address this issue- see Annex B (informative) Allocation procedures. Suggest revising this statement accordingly. 09/11/23 My point was that you should not use the term "Not stringent" because ISO 14044, 4.3.4.2 Allocation procedure requires ("shall") the application of a stepwise procedure: *ISO 14044, 4.3.4.2, The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure (Steps 1, 2 and 3).* I would agree with you if ISO would have read: ISO 14044, 4.3.4.2, The study should identify the processes shared with other product systems and deal with them according to the stepwise procedure (Steps 1, 2 and 3).	Update accordingly	We found nothing in Amd 2 that would be useful in this case.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
19	LB			Table 15	te	Table 15 0.60 kg recovered fiber/1.09 CBD or 1 kg CP Figure 1 0.62 kg (0.52+0.10) recovered fiber/1.10 CBD or 1 kg CP Figure 11 0.57 kg (0.48+0.09) recovered fiber//1.10 CBD or 1 kg CP Table 43 0.60 kg recovered fiber/ 1 kg CP. Table 44 0.613 kg recovered fiber per 1.09 CBD or 1kg CP Which factors are the correct ones?. Update the Figures/Tables/Text thoroughly to match the data in the LCA report.	Update accordingly	Updated	Closed
20	LB	51		Table 19	te	It reads: Emissions to Air Specify (process specific ONLY or Process specific and on-site fuel combustion).	Update accordingly	Updated	Closed
21	LB	77		Table 20	te	It reads: Emissions to Air Specify (process specific ONLY or Process specific and on-site fuel combustion).	Update accordingly	Updated	Closed
22	LB	91	5.2.4		te	1. GW,FF - is not specified. 2. Fix the GWPs below to IPCC AR6 GWPs ~~1, 30, and 265~~ the GWPs for CO2, CH4 and N2O (in kg CO2 eq./kg);	Update accordingly	Updated	Closed
23	LB			Table 27	te	Add a footnote: Renewable primary energy demand - excludes feedstock. It is missing.	Update accordingly	Updated	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
24	LB	147		Table 43	te	Table 43 0.60 kg recovered fiber/ 1 kg CP. Figure 1 0.62 kg (0.52+0.10) recovered fiber/1.10 CBD or 1 kg CP Figure 11 0.57 kg (0.48+0.09) recovered fiber//1.10 CBD or 1 kg CP Table 15 0.60 kg recovered fiber/1.09 CBD or 1 kg CP Table 44 0.613 kg recovered fiber per 1.09 CBD or 1kg CP Which factors are the correct ones?. Update the Figures/Tables/Text thoroughly to match the data in the LCA report.	Update accordingly	Updated.	Closed
25	LB	148		Table 44	te	Table 44 0.613 kg recovered fiber per 1.09 CBD or 1kg CP Table 43 0.60 kg recovered fiber/ 1 kg CP. Figure 1 0.62 kg (0.52+0.10) recovered fiber/1.10 CBD or 1 kg CP Figure 11 0.57 kg (0.48+0.09) recovered fiber//1.10 CBD or 1 kg CP Table 15 0.60 kg recovered fiber/1.09 CBD or 1 kg CP Which factors are the correct ones?. Update the Figures/Tables/Text thoroughly to match the data in the LCA report.	Update accordingly	Updated.	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
26	LB	150		Figure 48		Figure 48 1. Figure shows S3= +0.21 kg C The formula shows = +0.19 kg C (not 0.21). Outputs + Change in stocks = 0.28 + 0.05 + 0.19 + 0.01 + 0.007 + 0.011 + 0.022 = 0.57 kg C Update the Carbon Balance and/or Figure 48. 2. Fix the error below Impact of Biogenic CO2, Flow Accounting (F) F = (0.28 + 0.05 + 0.01 + 0.007 + ~~0.0011~~) - 0.55 = -0.20 kg C Fix ~~0.0011~~ to 0.011 kg C	Update accordingly	Figure and calculations updated	Closed
27	LB	151		Figure 49		Figure 49 1. Impact of Biogenic CO2, Flow Accounting (F) Calculations contain data that are not supported by Figure 49. F = 0.02 + 0.06 + 0.01 + 0.001 + 0.003 - 0.02 = -0.08 kg C ? Similar to Figure 48 calculations, shouldn't the calculations be:? F= 0.012+0.09+0.01+0.007+0.011- 0.014=0.116 please advise and update	Update accordingly	Figure and calculations updated	Closed
28	LB	157		Table 46	te	Table 46- There is a mix of SI with non-SI units, which could lead to errors. 1. Provide a footnote to clarify what "st" and "odst" stand for. 2. "tons' - specify short or metric tons.	Update accordingly	Done	Closed
29	LB			References	ge	Update ISO. (2006a). ISO 14040/Amd.1:2020 Environmental management — Life cycle assessment — Principles and framework. Geneva: International Organization of Standardization.	Update accordingly	Done	Closed
30	LB			References	ge	Update ISO. (2006b). ISO 14044/Amd.1:2017/Amd2:2020 – Environmental management — Life cycle assessment — Requirements and guidelines. Geneva: International Organization for Standardization.	Update accordingly	Done	Closed

Index	Initials	Page number	Clause/subclause	Par/Fig/Tab	Type	Comment	Recommendation	Response	Status Closed/Open
31	LB			Final comments	ge	1. Section 10.4 reads: The general conclusions of the comparison were shown to be unaffected? by the limitations of the study. Recommend the following adjustment that uses ISO 14040/44 terminology. The general conclusions of the comparison were shown not to be significantly (>10%) affected by the limitations of this study. 2. Figure 49: Fix the error below Impact of Biogenic CO2, Flow Accounting (F) F = (0.28 + 0.05 + 0.01 + 0.007 + ~~0.0011~~) - 0.55 = -0.20 kg C Fix ~~0.0011~~ to 0.011 kg C 3. Based on the statement on page 90, I suggest the following modification of the sentence on page 18 below for accuracy: Except for the greenhouse gas emissions from land-use change, impacts on land use and biodiversity were not quantified as no consensus method is suitable for forest management. 4. Since ISO 21930 is quoted twice on the LCA report, you might want to add it to the list of references- Appendic J. *ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.* 5. Technical Summary should include high-level Conclusions, Limitations and Recommendations. Recommend adding Limitations and recommendations in the TS. 6. Update the report date from ~~July~~ September 2023.	Update accordingly	1. Done. 2. Done 3. Replaced by Impacts on biodiversity 4. Added. 5. Added. Recomendations also added in section 10.4. 6. Corrected.	Closed

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