2010 STATUS QUO FOR LIFE CYCLE INVENTORY AND ENVIRONMENTAL IMPACT ASSESSMENT OF WOOD-BASED PANEL PRODUCTS IN GERMANY

*S.K. Diederichs**

Research Associate
Thuenen Institute of Wood Research
21031 Hamburg, Germany
E-mail: stefan.diederichs@ti.bund.de

(Received December 2013)

Abstract. Considering the importance of the German wood-based panel industry, the current status of available life-cycle inventory (LCI) data for these products is quite unsatisfying. In this study, detailed disaggregated LCI and environmental life-cycle assessment (LCA) data and variation in data on production of the core products of the German wood-based panel sector are given. The data suit a wide range of applications and are transparently documented, allowing consistent combination with other raw data sets. The data are analyzed in terms of sensitivity of environmental impacts to the variations in LCI. Also, specific advice is given to LCA practitioners on how to narrow the presented variations with respect to the environmental impact category they are interested in. Results are presented for the typical midpoint environmental impact categories excluding toxicity indicators. For the latter, the relevant data gaps are discussed.

Keywords: Life-cycle inventory, LCI, life-cycle assessment, LCA, wood-based panels, energy, emissions, carbon.

INTRODUCTION

With the initial basic concept of moderating the anisotropic nature of solid wood through homogenization, wood-based panels (WBP) have come a long way through technical development. Today, the worldwide annual production of about 275 Mm^3 of WBP (FAO 2013) offers an almost continuous covering of any possible compromise among mechanical, optical, and emission properties that can be influenced by particle size and orientation, type of adhesives and additives, processing parameters, and panel dimensions.

Based on figures from EPF (2012) and FAO (2013), the five biggest producers of WBP are China with 38% of the world production, followed by the US (11%), Germany, Russia, and Canada with 4% each. About 21% of the world production is from the European Union (EU). Compared with world production, which is split into fiberboard, particleboard, and plywood with approximately 1/3 each, EU and Germany have large production volumes of fiberboard and particleboard with 93 and 98% of total production, respectively.

German WBP production of 12 Mm^3 in 2011 was composed of 48% particleboard, 30% dry-process fiberboard, and 10% oriented strandboard. In addition, 6% of the production was hardboard (high-density fiberboard from wet process), 4% softboard (low-density fiberboard from wet process), and 2% plywood panels (EPF 2012; FAO 2013).

Environmental life-cycle assessment (LCA) has been conducted for all typical WBP. In Spain, Rivela et al (2006, 2007) conducted LCA for particleboard (PB) and dry-process fiberboard (FB) by analyzing one Spanish PB plant and two Spanish as well as one Chilean FB production facilities. (EPF [2007] identifies a total of 14 PB producers and 7 FB producers in Spain in 2005.) Kline (2005) analyzed four production facilities for oriented strandboard (OSB) in the southeast region of the US (from a total of 22 in this region). Wilson (2008, 2010b, 2010c) surveyed five PB and four FB manufacturing mills

* Corresponding author

Wood and Fiber Science, 46(3), 2014, pp. 340–355

in 2004, representing 23 and 27% of the total US production. The latest results were published by Silva et al (2013) who analyzed three Brazilian PB manufacturing mills that used eucalyptus as the wood resource.

In Germany, Frühwald et al (2000) conducted an analysis of five PB and three FB production lines as well as a literature-based assessment for production of OSB. Data were gathered between 1997 and 1999. From then until today, German production of PB decreased by 40% and plywood production by 50%, whereas production of FB increased by 125%. No relevant volume of OSB was produced in Germany in those years.

Considering the importance of the German WBP industry to the European and world market, the current status of publicly available, transparently documented, and up-to-date inventory data for these products is quite unsatisfactory. LCA practitioners analyzing WBP from German producers used in construction, packaging, or furniture have to either use old or undocumented data or data from a different geographical context.

This study aims to supply average detailed life-cycle inventory (LCI) and environmental LCA data and variation in data on production of the core products of the German WBP sector. For data to be useful, they should be basically disaggregated, allowing a wide range of applications, and should be transparently documented, allowing a consistent combination with other raw data sets. The results of this study should thoroughly fill the described data gap.

DATA AND METHODOLOGY

Functional Units

The most relevant products of the German WBP industry in terms of production volume are PB, FB, and OSB. In the case of PB and FB, the panels are sometimes laminated with a decorative layer, typically melamine-treated paper.

Functional units represent the supply of 1 m^3 to the factory gates of the products listed in Table 1. The functional unit PBm is defined to analyze the additional emissions that occur as a result of a melamine face. Table 2 gives an overview of the average material content and density of the products behind the functional units.

System Boundaries

Several different system boundaries were defined for the analysis (Fig 1). For the classic cradle-to-gate LCA, the system boundaries include all information from the supply of raw materials to the finished product at the gates of panel production. For the gate-to-gate LCI, the system boundary includes only foreground data of the production.

To simplify the trace of carbon flows in biomass, the supply of wood (background, forest/sawmill/transport) was separated from the supply of everything else (background, panel production).

Foreground Data

Foreground data were primarily gathered during the OekoHolzBauDat project, which was launched

Table 1. Functional units of the life cycle inventory and their names used in this study.[a]

Name	Group	Description
PBr	PB	Production of raw (nonfaced) PB based on the weighted production volumes of industrial partners
PBm		Production of melamine-faced PB based on the weighted production volumes of industrial partners; the average thickness as relevant for the melamine face is 18.7 mm including melamine face
OSB		Production of raw OSB
MDF	FB	Production of raw MDF with medium based on the weighted production volumes of industrial partners
HDF		Production of raw MDF with high density based on the weighted production volumes of industrial partners

[a] PB, particleboard; PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; FB, fiberboard.

Table 2. Functional units in terms of material content and mass (1 m^3).[a]

Content (kg)	PBr	PBm	OSB	MDF	HDF
Wood and water					
Stem wood and residues (odm)	428.1	415.7	530.9	590.3	669.3
Recovered wood (odm)	109.5	115.2	—	—	—
Water	37.6	37.2	27.0	47.0	61.7
Adhesive and others					
Adhesives	56.3	53.5	30.8	95.6	113.3
Additives	2.9	2.5	11.3	4.7	5.6
Lamination	—	32.9	—	—	—
Total	634.4	657.0	600	737.5	849.9
Total (kg odm)	596.8	619.8	573	690.6	788.2

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; odm, oven-dry mass.

in 2009 (survey was conducted for 3 yr in which 17 panel mills were analyzed by surveys and site visits). In addition to results from the conducted surveys, the foreground data also include calculated results. On-site emissions at panel facilities mainly arise from diesel, combustion of fossil fuels and wood fuel, pressing, and drying. Emissions from burning of wood are modeled as a function of filter technique, size, and fuel type based on Reitberger et al (2001), Speckels (2001), Tsupari et al (2005), Kaltschmitt and Hartmann (2009), and Böhmer et al (2010). Emissions from drying and pressing at the panel manufacturing plant were calculated based on Milota (2000) and Wilson (2010a).

Background Data

Specific background data for sawmill byproducts are also calculated on the basis of surveys conducted during the ÖkoHolzBauDat project (Rueter and Diederichs 2012). The methodology follows the rules described by Diederichs (2014).

Generic background data for forestry operations was taken from Schweinle (1996) and Albrecht

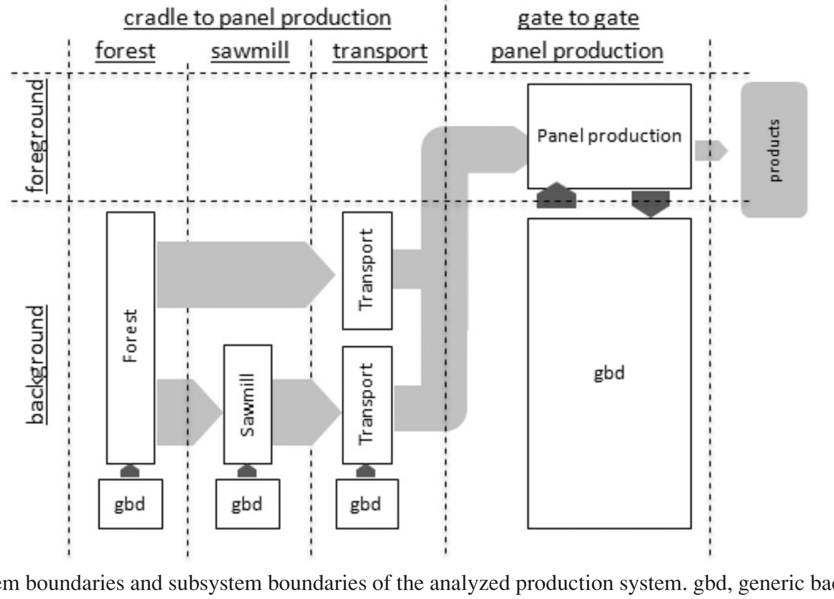

Figure 1. System boundaries and subsystem boundaries of the analyzed production system. gbd, generic background data.

et al (2008). Transport models are based on Borcherding (2007) and the European Commission (2010a). The electricity grid mix model is based on AG Energiebilanzen e.V. (2010) and PE International (2012). Indicated emissions were 572 kg CO_2-Eq/kWh, which is in the range of official data from UBA (2012), and in that study, greenhouse gas emissions of 577 kg CO_2-Eq/kWh for 2009 and estimated 562 kg CO_2-Eq/kWh for 2010 were reported. Background data for adhesive production were primarily based on Zeppenfeld and Grunwald (2005) for the production starting from basic chemicals and PE International (2012) for the production of basic chemical materials. Especially for the different mol ratios of formaldehyde and urea and phenol and melamine, feedback from experts from the panel industry completed the data. For formaldehyde-based resins, results from Wilson (2009) were used for plausibility checks. The detailed models and mol ratios are documented in Rueter and Diederichs (2012). The model used for OSB production was primarily based on information on the production of polymethylenediisocyanate (pMDI). The environmental impacts were calculated according to Zeppenfeld and Grunwald (2005), and a raw data set for diphenyl-methan-4.4-diisocyanate was supplied by PE International (2012).

Allocation Principles

Many forms of wood resources are used for panel production. Logs or sawmill residues as well as industrial wood residues and recovered wood can be used as material resources. For energy purposes, bark and residues from landscaping are used as well. Some of these wood resources are byproducts of other production systems. For a cradle-to-gate assessment of WBP, emissions that occur in those other production systems need to be partially allocated to those systems and the systems being studied. This calculation step is one of the most discussed aspects in LCA. It has a large effect on the results of the study (Jungmeier et al 2002) and the choice of the allocation type depends mainly on the purpose of the results (European Commission 2010b).

In this study, LCI is calculated from gate to gate. In other words, the LCI includes all flows that cross the boundary of the foreground gate-to-gate panel production system (Fig 1). Because all byproducts of the panel production are directly used as fuel or are recycled internally in a closed loop, no allocation procedure is needed for this step. Hence, the LCI results at the foreground gate-to-gate boundary are free of allocation procedures and can be used in a wide range of applications. An exception is when a combined heat and power plant is on-site. In this case, the power plant was considered outside the foreground system boundaries but inside the background gate-to-gate boundaries as reasoned by Diederichs (2014). The allocation procedure then was based on exergy.

In contrast, LCA results were calculated from cradle to gate. They include all subsystems shown in Fig 1. Hence, allocation procedures were necessary.

Forestry operations yield small-diameter logs, mostly used for pulp, paper, panels, and energy, as well as sawlogs with larger diameters. The choice for a procedure to allocate emissions from forestry operations to those products is based on recommendations of EN 15804 (EN 2012), in which allocation shall be based on economic values if the difference in revenue from the coproducts is high (more than 25%). Based on prices listed in NRW (2011) and StELF (2011) as well as deviation of assortments from the base scenario of Polley and Kroiher (2006), differences in revenue are 26% for pine and beech, 32% for oak, and 65% for spruce. Hence, the price of the products was chosen as the basis for allocation. Based on an LCA conducted by Zimmer (2010), the production of forest chips was estimated to have 17% of the environmental impact of small-diameter spruce. Bark from forest and landscaping wood was assumed to have the same impact as forest chips (always based on oven-dry mass of biomass).

Sawmill byproducts used in the WBP industry are assumed to arise exclusively from the milling process in the sawmills. Hence, the environmental impact is identical to that of green sawnwood described in Diederichs (2014), except that milling impacts are allocated to the byproducts instead. Allocation was based on price.

Recovered wood for material or fuel use does not carry an environmental burden when it enters the system. Only its inherent characteristics such as heating value and carbon content are traced in the flow. The reason for this is the definition of the "end-of-waste-state" in EN (2012), which is located at the retailer of the recovered wood (Rueter and Diederichs 2012). Hence, all process steps before this are allocated completely to the former product system. However, the environmental impact of transportation from the retailer of recovered wood to the panel factory is taken into account.

Flows of Carbon in Biomass

In contrast to allocation of, for example, electricity and thermal energy to products and byproducts (which is based on economic value), the wood resources are allocated to products and byproducts based on oven-dry mass as recommended by ISO 14044 (ISO 2006). Therefore, inputs and outputs of the material inherent characteristics of a production system are balanced. This also refers to the carbon content of the biomass. Figure 2 shows the carbon balance in a life cycle of a typical WBP. Wood resources used either as fuel or material are accounted for as "negative" emissions. If wood is burned on-site or at the end of its service life, emissions arise from combustion. If the wood is transferred to a second production system without being burned (in the case of recovered wood), its inherent characteristics are subtracted from the first system and added to the next. No amount gets lost.

The amount of carbon from biomass is causally determined by the wood mass within the products (Table 2) and the wood mass burned during production (Table 3). Figure 2 clarifies why, mathematically, carbon dioxide emissions from biomass vanish in cradle-to-grave assessments. In contrast, cradle-to-gate totals as published in this study actually include "negative" emissions from wood use. For transparency reasons, carbon flows of biomass were not taken into account in the environmental impacts assessment here. They would superimpose fossil-based emission while not giving any additional information.

Cut-Off Rules, Assumptions, and Data Gaps

Decisions regarding which flow to include in the LCI were based on previously published LCA results for WBP (see Introduction) and a sensitivity analysis performed by Rueter and Diederichs (2012). Hence, every flow exceeding 1% of an indicator result was included, whereas all neglected flows did not exceed 5% of this indicator result. Flows that were below this threshold but were known anyhow were included.

Assumptions were made regarding capital goods such as buildings and machinery. They were not included in terms of their production, because the associated impacts were assumed to not exceed 1% of the total. Further assumptions were made in context with adhesives and additives. As shown by comparing Table 2 with Table 3, the model defines that all flows listed under the categories adhesives and additives in Table 3 are assigned to the functional units in Table 2 with the identical amounts. Because no detailed data were available on the internal waste flows of the companies, all inputs of adhesives and additives were assumed to leave the company as content of the respective product.

Data gaps occurred in context with the wrapping material for the equipment. Hence, in the model, it was assumed that the equipment entered the company without any wrapping. The emission model for combustion of wood fuel was based on literature data. Comparing those with data listed by Rentz et al (2009), gaps occurred for emissions of selenium, polychlorinated biphenyls, polychlorinated dibenzodioxins, benzo(a) pyren, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene, and hexachlorbenzene. Implications of the described data gaps are discussed later in the text.

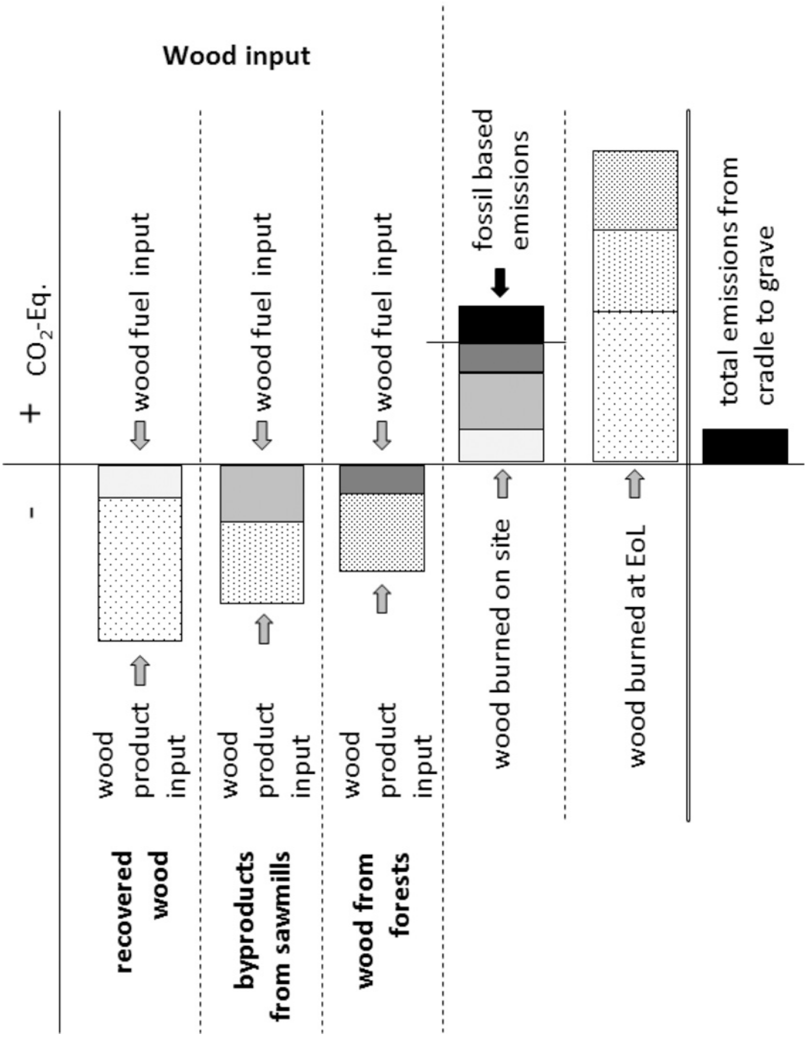

Figure 2. Typical carbon balance of wood-based panels. EoL, end of life.

Impact Assessment

The impact assessment covers six impact categories defined in EN (2012), which are global warming potential for 100 yr (GWP100), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), stratospheric ozone depletion potential (ODP), and abiotic resource depletion potential (ADP). For ADP, two subcategories exist. ADPe describes the depletion of elements of nonfossil resources, and ADPf describes the depletion of fossil fuels. Classification and characterizations of emissions are based on definitions published by Universiteit Leiden (2010). Carbon dioxide emissions evolving from oxidization of carbon contained in biomass and photosynthetic capture of carbon dioxide to carbon contained in biomass are not included in the GWP100 category for the reason previously described.

The impact assessment was conducted from cradle to gate, covering the complete system shown in Fig 1. Although the LCI from gate to gate was the main output of this study, the impact assessment was used to analyze the sensitivity of the

Table 3. Life-cycle inventory for functional units from cradle-to-gate, foreground system.[a]

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Inputs						
Wood as material						
Stem wood	(kg)	86.9	84.8	708.0	414.0	254.1
Industrial residues	(kg)	404.7	402.4	—	398.6	614.4
Recovered wood	(kg)	125.8	135.0	—	—	—
Fuels						
Wood residues	(MJ)	465.1	746.5	1682.8	2,644.4	2030.1
Recovered wood	(MJ)	1152.5	598.6	—	3321.1	3838.8
Fuel oil	(MJ)	17.2	5.3	5.2	70.3	34.7
Gas	(MJ)	69.0	112.9	404.1	1.9	2.5
Diesel	(kg)	0.6	0.7	0.6	0.8	0.7
Electricity (from grid)						
Process	(kWh)	102.4	121.1	120.9	297.6	301.1
Equipment						
Lubricants and engine oil	(g)	55.6	61.4	55.6	260.4	260.4
Tools (steel)	(g)	63.3	69.2	13.9	133.7	133.7
Water	(kg)	202.7	317.4	499	1107.2	1107.2
Adhesive						
UF	(g)	49.0	44.8	—	95.6	113.3
MUF	(g)	5.0	8.7	9.7	—	—
PF	(g)	0.4	—	—	—	—
pMDI	(g)	0.9	—	21.1	—	—
Additives						
Wax	(kg)	2.7	2.0	11.3	4.7	5.6
Fire retardant	(g)	195.8	517.1	—	—	—
Lamination	(kg)	—	32.9	—	—	—
Wrapping						
Polymers	(g)	160.7	205.2	50.7	197.4	197.4
Wood	(kg)	5.2	5.2	2.0	21.6	21.6
Paper and cardboard	(g)	129.9	123.6	230.9	519.6	519.6
Steel	(g)	57.7	62.8	251.4	647.0	647.0
Outputs						
Product (wrapped)						
Product	(m^3)	1.0	1.0	1.0	1.0	1.0
Byproducts						
Residues	(kg)	79.8	91.2	177.1	222.2	199.2
Waste						
Waste	(kg)	0.1	0.1	0.1	0.4	0.4
Water	(kg)	202.7	317.4	499.0	1107.2	1107.2
Emissions (direct)						
CH_4	(g)	34.7	36.1	79.7	72.7	68.2
CO	(g)	66.0	63.2	68.9	219.1	212.3
CO_2 (from fossil fuels)	(kg)	8.3	9.9	26.9	6.6	3.7
N_2O	(mg)	456.0	426.4	705.6	1437.8	1369.6
NMVOC	(g)	126.6	128.4	103.5	224.1	238.6
SO_2	(g)	13.0	13.6	19.0	31.7	29.0
NO_x	(g)	164.6	161.3	180.3	520.9	502.2
Pb	(mg)	291.0	257.9	294.8	1085.2	1061.4
Cd	(mg)	0.7	0.6	0.7	2.4	2.4
Hg	(μg)	58.9	53.1	62.9	211.2	205.2
As	(mg)	13.6	12.1	13.8	50.8	49.7

Table 3. *Continued.*

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Cr	(mg)	12.5	11.1	12.7	46.6	45.6
Cu	(mg)	140.6	124.6	142.4	524.4	512.9
Ni	(mg)	69.6	61.7	70.4	259.4	253.6
Zn	(mg)	0.3	0.3	0.3	0.9	0.9

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; UF, urea–formaldehyde; MUF, melamine urea–formaldehyde; PF, phenol–formaldehyde; pMDI, polymethylenediisocyanate; NMVOC, nonmethane volatile organic compound.

evaluated impact categories toward variations in the LCI values caused by variations among companies and products and those caused by uncertainties in the data.

RESULTS

General

Table 3 shows all results of the LCI as average values weighted by production volume of all surveyed producers of a product. Table 4 shows the LCA results for each impact category from cradle to gate and the share of each subsystem defined in Fig 2.

In general, large shares of environmental impacts resulted from the gate-to-gate background system (supply of all products but wood) except for POCP. Here, on-site emissions were responsible for the greatest share. Regarding the wood supply alone, forestry and transport took the leading role for all indictors except ODP. Here, the share of impacts from sawmills played a major role. ODP shares were dominated by electricity consumption, which is naturally low for forestry and transport operations.

Environmental impact data were analyzed to better understand the environmental relevance of variations in LCI data. Hence, for every LCI category, a corresponding LCA background system was defined. Figure 3 shows impacts that can be connected to each category of the inventory of the cradle-to-gate impact assessment of PBr and FB. In Fig 3, the upper beam in each category indicates the PBr impact variation and the lower beam indicates variation in FB results. The dots indicate the absolute results based on the average values in the inventory for PBr (white upper dot), OSB (black upper dot), medium-density fiberboard (MDF) (white lower dot), and high-density fiberboard (HDF) (black lower dot). Gray-marked LCI categories (axis of ordinate) are identified to have variations causing high impact on the cradle-to-gate results. Those in particular are among the following description of variations. Indicator ADPf is not part of Fig 3 because its variations are very close to variations in GWP.

Wood as Material

Wood for material use is supplied to panel producers in the form of logs, industrial residues, or recovered wood. The latter is only used in the production of conventional PB representing an average of 20% of the wood material input (based on oven-dry mass). Residues are used for all panels based on particles and fibers except OSB. For OSB, logs are used exclusively. The corresponding LCA background system was defined to include the supply of wood, including all forestry, sawmilling, and transport operations necessary.

The supply of wood plays a significant role in the level of emissions classified to AP, EP, and GWP (compare total share of forest, transport, and sawmill in Table 4). Large variations within the impact factors of this LCA background system are influenced by variations in the amount of emissions. Sources of emissions are burning of diesel during forestry operations, road transport from forests to sawmill and from sawmill to panel production, and direct transport from forests to panel production. Panel density has a primary influence on the amount of emissions. Density variations between 600 and 730 kg/m^3 for PB and between 730 and 880 kg/m^3 for FB

Table 4. Life-cycle assessment results with share of each subsystem boundary to each impact category result (%).[a]

Flow	Unit	PBr	PBm	OSB	MDF	HDF
Foreground, gate to gate						
GWP	(%)	6	5	14	4	3
AP	(%)	21	14	11	29	26
EP	(%)	15	10	18	24	22
POCP	(%)	84	74	86	80	79
ODP	(%)	0	0	0	0	0
ADPe	(%)	0	0	0	0	0
ADPf	(%)	4	3	8	1	0
Background, gate to gate						
GWP	(%)	83	88	82	86	85
AP	(%)	57	70	82	49	49
EP	(%)	68	78	70	57	58
POCP	(%)	11	21	13	12	12
ODP	(%)	95	97	100	98	97
ADPe	(%)	99	99	100	99	99
ADPf	(%)	88	90	89	91	90
Sawmill						
GWP	(%)	1	1	0	1	1
AP	(%)	1	1	0	0	1
EP	(%)	0	0	0	0	0
POCP	(%)	0	0	0	0	0
ODP	(%)	3	2	0	2	2
ADPe	(%)	0	0	0	0	0
ADPf	(%)	1	1	0	1	1
Transport						
GWP	(%)	4	3	2	5	5
AP	(%)	7	5	2	12	13
EP	(%)	5	4	4	10	11
POCP	(%)	1	1	0	4	4
ODP	(%)	0	0	0	0	0
ADPe	(%)	0	0	0	0	0
ADPf	(%)	3	2	1	4	5
Forest						
GWP	(%)	6	4	3	4	5
AP	(%)	15	10	5	9	11
EP	(%)	11	7	9	8	9
POCP	(%)	4	4	1	4	4
ODP	(%)	1	1	0	1	1
ADPe	(%)	0	0	0	0	0
ADPf	(%)	5	3	2	4	4
Totals (cradle to gate)						
GWP	(kg)	217	328	318	406	429
AP	(kg)	0.50	0.72	1.06	1.10	1.15
EP	(g)	152	222	145	299	321
POCP	(g)	248	285	646	387	418
ODP	(mg)	24	43	22	58	59
ADPe	(mg)	215	246	989	280	315
ADPf	(MJ)	3665	5041	5817	6429	6897

[a] PBr, raw, nonfaced particleboard; PBm, particleboard with melamine face; OSB, oriented strandboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; ADPe, abiotic resource depletion potential elements of nonfossil resources; ADPf, abiotic resource depletion potential of fossil fuels.

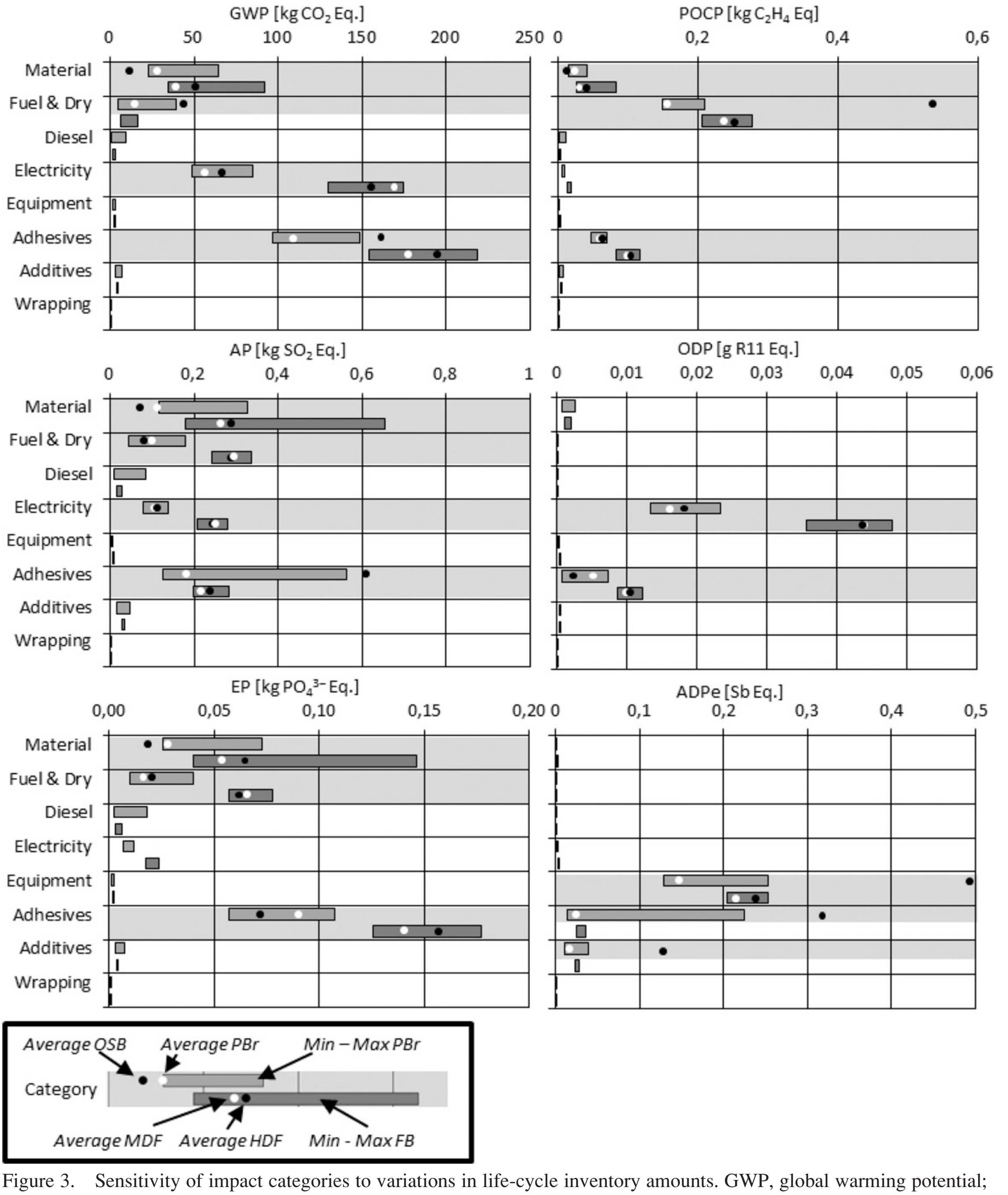

Figure 3. Sensitivity of impact categories to variations in life-cycle inventory amounts. GWP, global warming potential; POCP, photochemical ozone creation potential; AP, acidification potential; ODP, ozone depletion potential; EP, eutrophication potential; ADPe, abiotic resource depletion potential elements of nonfossil resources; OSB, oriented strandboard; PBr, raw, nonfaced particleboard; MDF, medium-density fiberboard; HDF, high-density fiberboard; FB, fiberboard.

result in quite linear variations in impact. Furthermore, variations in the material mix influence results. Panels with a high share of recovered wood have lower impacts than those that incorporate residues or logs. In the latter case, logs have lower impacts than residues. Variations in transport distances are low in the case of wood supply for PB production (80-120 km) and much higher for FB production (60-250 km). For the latter, transport distances may heavily eclipse the influence of density but play a minor role for variations in PB results.

Fuel and Drying

Thermal energy is predominantly generated by the combustion of wood fuels in the form of residues or recovered wood. The choice between residues and recovered wood is mainly influenced by the installed combustion technique and emissions threshold values, respectively. Fossil fuels are used only in exceptional circumstances or if thermal energy is not the driving force of production costs. The drying procedure, in which most of the generated heat is used, is responsible for most volatile organic compound (VOC) emissions on site. The corresponding LCA background system for fuel supply, combustion, and the drying process was defined to cover all emissions from supplying and burning of any fuel used to generate thermal energy as well as all direct emissions from drying.

Environmental impacts are primarily expressed as GWP, AP, EP, and POCP. Greenhouse gases mainly derive from combustion of fossil fuels. Nitrogen oxides and sulfur dioxide, dictating results for AP and EP, originate from combustion of wood fuels. Emissions of VOC from the drying procedure dictate the POCP indicator.

Naturally, variations in the pure amount of fuels burned have a large influence on variations in impacts. In the case of PB, between 872 and 2700 MJ/m^3 of energy input is needed, whereas 5100-6200 MJ/m^3 is needed for FB. The surveyed companies that produce PB used up to 5% fossil fuels, whereas surveyed FB production mills used wood fuels only. Therefore, variations in emissions of greenhouse gases were higher for PB than for FB.

VOC emissions were calculated on the basis of the total dried wood mass, which obviously resulted in good linearity between emissions and panel density. Only variation in yield after drying leads to disturbance of this linearity. Because little data for OSB production were available, it was assumed that all wood that entered the process was dried, indicating the worst case possible.

Electricity

On average, production of PBr consumes about 100 kWh/m^3 with variations from 80 to 140 kWh/m^3. For FB, electricity use of about 300 kWh/m^3 is average with variations from 230 to 310 kWh/m^3. The corresponding LCA background system was defined to include all emissions resulting from the production of electricity. Because a general electricity mix was used for the model, variations within the indicator results are linear to quantitative differences in electricity consumption of panel production. Global warming, resulting from electricity production, driven almost totally by carbon dioxide (95% of the impact) and acidification, sulfur dioxide (73% of the impact), and nitrogen oxides (27% of the impact), primarily influences the total cradle-to-gate impacts of panel production. Emissions leading to depletion of stratospheric ozone (ODP) result from use of chlorofluorocarbons in context with cooling during enrichment of uranium. Electricity consumption is the overall driving force of this latter indicator.

Adhesives

Generally, thermosetting adhesives are used in panel production. For PB, urea–formaldehyde adhesives are used predominantly. For FB production, the surveyed companies used urea–formaldehyde adhesives exclusively. OSB is typically produced by applying isocyanate-based adhesives. Average LCI data indicate that about 50 kg/m^3 are used for conventional PB, about 100 kg/m^3 are used for FB, and about 30 kg/m^3 are applied for OSB. The corresponding LCA background system comprises the production, supply, and curing of the adhesives used.

The panels analyzed in this study represent a weighted average of the surveyed production mix. Hence, the functional units describe average products with several types of adhesives, never being used in one product in reality. Therefore, the discussion about variations of environmental impacts caused by application of different adhesives focuses on the specific adhesive types rather than the functional units. Figure 3 indicates a distinctive sensitivity of impacts to variation in adhesive properties in every category. Particularly large variations are visible for GWP, AP, and EP.

Specific greenhouse gas emissions associated with formaldehyde-based adhesives ranged from 1.8 to 2.5 kg CO_2-Eq/kg. In the case of a melamine backing of the urea–formaldehyde-based adhesives (MUF), the melamine is responsible for about 0.5 kg CO_2-Eq/kg, depending on the amount added. In PB production, 46-66 kg/m^3 of formaldehyde-based resins are used, and for FB, 88-139 kg/m^3 are used. Specific greenhouse gas emissions as a result of pMDI application are about 4 kg CO_2-Eq/kg, mainly resulting from the production of aniline, one of the three base chemicals for production of pMDI, in addition to formaldehyde and phosgene. Typically, in the case of pMDI, less adhesive per cubic meter of panel is applied than for formaldehyde-based resins. About 35 kg/m^3 is applied in the manufacture of conventional PB, and 21 kg/m^3 is applied in the manufacture of OSB. Little amounts of MUF are typically used for the decking layer when pMDI is applied. Peak greenhouse gas emissions from OSB manufacture result from the worst case estimation for OSB production. This will be further discussed in the Uncertainties section.

Variation in emissions leading to AP is particularly great in PB production. The reasons are the high amounts of sulfur dioxide emissions from production of phenol used in phenol–formaldehyde-based adhesives and to an even larger extent from production of pMDI. Therefore, urea-based resins dominate at the lower part of the variation beam, phenol-based resins rank in the middle, and pMDI resides at the top.

This is inversely the case for emissions leading to EP. Urea-based resins reside at the top because of the high amount of emissions of ammonia to water during production of urea and melamine. Phenol-based resins are again in the middle, whereas production and use of pMDI result in the lowest EP compared with other adhesives.

Regarding ADPe, the phenol-based and pMDI adhesives are at the very top of the indicated range.

Others

Diesel consumption in forklifts and other machines is very similar for PB, OSB, and FB. The amounts do not result in relevant impacts in the LCA background system “Diesel,” including fuel supply and emissions from combustion.

The total mass of energy-related emissions from equipment used during production of PB and OSB adds up to about 60 g/m^3, whereas fiber-based panels produce about 260 g/m^3. The production of fiber-based panels consumes about four times as much lubricants as the PB production process. With regard to the ADPe indicator, some panel producers use more steel for tools than others, a factor that influences variability in emission values.

Wax is used for panels that need to last in humid conditions. Therefore, large amounts are used for OSB. However, the amounts do not result in relevant impacts on the LCI background systems “Equipment” and “Additives.”

About 160-200 g/m^3 of foil is used to wrap 1 m^3 of PB or FB. For PB, about 125 g of cardboard and 60 g of steel are needed as well. Packaging of fiber-based panels requires about 4 times the amount of cardboard and 10 times the amount of steel. For OSB, less foil but more cardboard and steel is used compared with PB. Also, the amounts do not result in relevant impacts on the

LCI background system "Wrapping," comprising supply and waste management of the wrapping material.

Melamine Lamination

Generally, PB and FB can both be surfaced with melamine paper. The analyzed process for PB can be transferred to melamine-coated FB. On-site, the process consumes about 11 kWh/m^3 of electricity and 100 MJ/m^3 of heat. The melamine lamination has an average mass of 32.9 kg/m^3, which results in 308 g/m^2 of laminated area or 616 g/m^2 if both sides are laminated.

In total, the lamination process (including lamination material) is responsible for about 24-33% of the cradle-to-gate results of PBm for GWP, AP, EP, ADPf, and ODP. POCP and ADPe make up 11-12% of the total cradle-to-gate results. Regarding the actual source of emissions from lamination, the production of the lamination material is responsible for at least 89% of all indicator results. For production of melamine lamination material, electricity consumption, production of basic paper, and production of the melamine-based prepolymer together are responsible for 89-96% of the total emissions.

DISCUSSION

Uncertainties

Regarding wood combustion, uncertainties may arise from the literature-based model for all products. There are data gaps and data ranges to deal with.

The reported data gaps do not interfere with the impact categories declared in this study, because none of the emissions has an impact in those categories. However, if other indicators, especially those focusing on toxicity, are evaluated based on this data set, uncertainties may arise from the documented data gaps.

However, the data ranges do interfere with the impact categories declared in this study. Regarding uncertainties listed by Rentz et al (2009) and their impact in terms of wood combustion emissions by the WBP industry, the indicators AP, EP, and POCP are affected by large uncertainty as to emissions of NO_x, SO_2, and nonmethane VOCs. Uncertainties relevant for POCP results also arise from poor knowledge of VOC emissions from drying. Table 5 summarizes the uncertainties in LCA results that derive from uncertainties in emissions data from combustion and drying. For the latter, the impact of a 10% uncertainty on the LCA results was analyzed.

Table 5. Uncertainty in life-cycle assessment impact indicators as a result of uncertainty in data (%).[a]

Uncertainty	Emission factors	VOC from drying
Alternation range	EEA[b]	10
GWP	0-1.2	0-0.2
EP	0-14	<0.1
AP	0-27	<0.1
ODP	<0.1	<0.1
POCP	0-95	0-6.0

[a] GWP, global warming potential; EP, eutrophication potential; AP, acidification potential; ODP, ozone depletion potential; POCP, photochemical ozone creation potential; VOC, volatile organic compound; EEA, European Environmental Agency.
[b] Rentz et al (2009).

For wood supply, it was assumed that sawmill residues used in the panel industry arise exclusively from milling. This assumption was used to simplify the complex model of byproduct supply to the panels. In reality, other residues (eg planing residues) might be used as well. Because allocation is based on the economic value of products, significant impact accounting gaps do not occur when the amount of byproducts decreases while the value of the main products increases along the process value chain of solid wood products.

In the case of OSB, further uncertainties arise as a result of missing process-specific data. VOC emissions from drying may be substantially overestimated because it was assumed that all wood entering a plant was dried, although it might have been sorted out for combustion before drying.

Representativeness

Table 6 shows the production amount analyzed in comparison with total national production. Differentiation between total production of HDF

Table 6. Products and representativeness (fraction) of the analyzed volumes 2011.

	Production (1000 m^3)	
Products[a]	National[b]	Survey
PB	5750	4705
OSB	1200	—
FB	3600	652

[a] PB, particleboard; OSB, oriented strandboard; FB, fiberboard.
[b] EPF (2012).

and MDF was not possible on the basis of available data. Because the LCI for OSB relied on a survey of one company only, representativeness cannot be given because of confidentiality reasons. However, representativeness can be assumed to be 33% for OSB because all three German OSB plants have similar capacities. In conclusion, the representativeness achieved is fairly high compared with comparable studies listed in the Introduction.

Other Studies

Table 7 shows specific aspects of LCI results compared with other studies. For OSB, lower fuel consumption was calculated compared with data from Frühwald et al (2000) and Kline (2005). For FB, lower electricity consumption was measured compared with data from Frühwald et al (2000), Rivela et al (2007), and Wilson (2010b). However, in most cases, impact values are similar to those of other studies indicating good plausibility of the results.

Applying Life-Cycle Inventory Data

The LCI presented in this study can be used as a source of background data for various applications in need of environmental information regarding the production of WBP. The documented variations can be used to either express uncertainty as to results or model worst and best case scenarios. Alternatively, LCA practitioners can gather more specific data on a panel to narrow the variations for a specific impact indicator.

For GWP and ADPf results, information on adhesives, density, specific electricity consumption, type of fuel used for generation of heat, and transport distances can be helpful. In most cases, information on the three latter aspects is rather unlikely to be available at the product use level. In contrast, information on product density and applied adhesives is available in most cases. These two aspects also help to decrease variations in AP and EP results drastically. If information on electricity consumption is available, ODP results can be narrowed.

For POCP results, more information on drying emissions is needed. Nevertheless, the influence of density can be used to narrow variations also for POCP. Because of large uncertainties in nonmethane VOC emissions from fuel combustion, POCP results remain vague for any type of panel.

For ADPe, information on adhesive type and the amount of steel used helps to narrow variations. The indicator is pushed markedly upward if pMDI or it is used in panel manufacture.

In the case of FB or PB with melamine paper coating, the mass per unit area primarily determines the additional environmental impact.

CONCLUSION

This study presents disaggregated gate-to-gate LCI data for typical products of the German

Table 7. Different life-cycle inventory results (gate to gate) for production of panels compared with other studies.[a]

	Mass (kg)		Electricity (kWh)		Fuel (MJ)		Diesel (MJ)	
Product[b]	This	Other	This	Other	This	Other	This	Other
PBr	596	636-746	102	105-158	1704	1655-3112	26	16-18
OSB	573	610-649	121	130-207	2092	3000-3865	26	15
FB	691	615-741	298	353-415	6038	4211-8568	34	37-51

[a] Based on Frühwald et al (2000), Kline (2005), Rivela et al (2006, 2007), and Wilson (2010b, 2010c).
[b] PBr, raw, nonfaced particleboard OSB, oriented strandboard; FB, fiberboard.

WBP industry, with high representativeness. The presented data were discussed in terms of their relevance for several environmental impact categories starting with a gate-to-gate view toward a more complete cradle-to-gate assessment. Furthermore, the data were analyzed in terms of the sensitivity of environmental impacts to the variations in LCI, which were reasoned by variations among companies, products, and processes.

The results supply good background information for any type of environmental impact assessment in connection with WBP. On one hand, the data can be used as an average or worst case scenario if WBP only plays a minor role in the analyzed production system. On the other hand, this study supplies information on how to narrow variations in results if more precise data are needed. LCA practitioners can gather specific information described in this study to narrow the variations in results with respect to the environmental impact category they are interested in.

Reliable data are presented for the environmental impact categories GWP, AP, EP, ADPe, ADPf, and ODP. In the case of POCP, the impacts of uncertainties in emissions from wood combustion outweigh the impacts based on reliable information. Hence, more data are needed if POCP results will be looked at in detail. Nevertheless, with the data presented, a reasoned estimation and worst case scenario can be formulated even for POCP results for each product. For assessment of toxicity impacts based on the presented data, attention has to be paid to data gaps concerning dioxins and several other emissions listed in this study.

ACKNOWLEDGMENTS

Thanks to all companies that supplied data via questionnaires and during on-site visits. Thanks also to "Verband der Deutschen Holzwerkstoffindustrie e.V." (wood-based panel association) for their invaluable assistance in organizing communication networks between science and the German wood-based panel industry. Financial assistance for this research was provided by the Fachagentur Nachwachsende Rohstoffe (22028808). Special thanks to Sebastian Rüter and Johannes Welling for making this research possible.

REFERENCES

AG Energiebilanzen e.V. (2010) Auswertungstabellen zur Energiebilanz Deutschland, Daten für die Jahre 1990 bis 2009. AGEB, Berlin, Germany. 13 pp.

Albrecht S, Rueter S, Welling J, Knauf M, Mantau U, Braune A, Baitz A, Weimar H, Sörgel S, Kreißig J, Deimling S, Hellwig S (2008) Ökologische Potentiale durch Holznutzung gezielt fördern. Johann Heinrich von Thünen Institut, Institut für Holztechnologie und Biologie, Hamburg, Germany. 298 pp.

Böhmer S, Gallauner T, Gössl M, Krutzler T, Moser G (2010) Biomassefeuerungsanlagen, Im Leistungsbereich von 400 kW bis 10 MW. Umweltbundesamt GmbH, Wien, Germany. 76 pp.

Borcherding M (2007) Rundholztransportlogistik in Deutschland–Eine transaktionskostenorientierte empirische analyse. PhD thesis, Universität Hamburg, Hamburg, Germany. 266 pp.

Diederichs SK (2014) 2010 status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. Wood Fiber Sci 46(1):1-20.

EN (2012) EN 15804. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. European Committee for Standardization, CEN/TC 350—Sustainability of Construction Works, Brussels, Belgium. 50 pp.

EPF (2007) Annual report 2006–2007. European Panel Federation, Brussels, Belgium.

EPF (2012) Annual report 2011–2012. European Panel Federation, Brussels, Belgium. 328 pp.

European Commission (2010a) ELCD core database version II. Joint Research Centre–Institute for Environment and Sustainability, Brussels, Belgium. http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm (1 October 2010).

European Commission (2010b) ILCD handbook, general guide for life cycle assessment—Detailed guidance. European Commission, Joint Reserach Centre, Institute for Environment and Sustainability, Ispra, Italy. 414 pp.

FAO (2013) Wood based panels, production quantity, 2011. The Statistics Division of the Food and Agricultural Organisation of the United Nations, Domain Forestry, Forestry Production and Trade. http://faostat3.fao.org/faostat-gateway/go/to/home/E (5 July 2013).

Frühwald A, Scharai-Rad M, Hasch J (2000) Ökologische Bewertung von Holzwerkstoffen Schlußbericht März 2000 Ergänzt in den Bereichen Spanplattenrecycling und OSB-Bilanzen, Hamburg, Germany.

ISO (2006) Environmental management—Life cycle assessment—Requirements and guidelines, ISO 14044:2006. International Organization for Standardization. TC 204/SC5.

Jungmeier G, Werner F, Jarnehammar A, Hohenthal C, Richter K (2002) Allocation in LCA of wood-based products experiences of cost action E9. Int J Life Cycle Assess 7(6):369-375. www.springerlink.com/content/w5h3070684802251/ (30 August 2010).

Kaltschmitt M, Hartmann H (2009) Energie aus biomasse. M. Kaltschmitt, H. Hartmann, and H. Hofbauer, eds. Springer, Dordrecht, The Netherlands, Heidelberg, Germany, London, UK, New York, NY. 1054 pp.

Kline DE (2005) Gate-to-gate life-cycle inventory of oriented strandboard production. Wood Fiber Sci 37(Corrim Special Issue):74-84.

Milota MR (2000) Emissions from wood drying. Forest Prod J 50(6):10-20.

NRW (2011) Holzpreise NRW. Landesbetrieb Wald und Holz NRW. www.wald-und-holz.nrw.de/45Wald_und_Holz/20_Holzmarkt/10_Holzpreise/index.php (1 October 2011).

PE International (2012) GaBi 4 Software and GaBi Professional Database Version 4.131. PE International. Leinfelden-Echterdingen, Germany (available at http://www.gabi-software.com).

Polley H, Kroiher F (2006) Struktur und regionale Verteilung des Holzvorrates und des potenziellen Rohholzaufkommens in Deutschland im Rahmen der Clusterstudie Forst- und Holzwirtschaft. Bundesforschungsanstalt für Forst- und Holzwirtschaft Hamburg, Institut für Waldökologie und Waldinventuren, Eberswalde, Germany. 128 pp.

Reitberger F, Huber S, Streit A, Schmoeckel G, Ebertsch G, Stöttner A, Zell B (2001) Energetische Nutzung nachwachsender Rohstoffe. Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen, München, Germany. 77 pp.

Rentz O, Oertel D, Woodfield M, Stewart R (2009) Manufacturing industries and construction (combustion). Chapter 1.A.2. *In* EMEP/EEA air pollutant emission inventory guidebook 2009. European Environmental Agency, Copenhagen, Denmark. pp 1-34

Rivela B, Hospido A, Moreira MT, Feijoo G (2006) Life cycle inventory of particleboard: A case study in the wood sector. Int J Life Cycle Ass 11(2):106-113.

Rivela B, Moreira MT, Feijoo G (2007) Life cycle inventory of medium density fibreboard. Int J Life Cycle Ass 12(3):143-150.

Rueter S, Diederichs S (2012) Ökobilanzbasisdaten für Bauprodukte aus Holz. Thünen Institut, Hamburg, Germany. 299 pp.

Schweinle J (1996) Analyse und bewertung der forstlichen produktion als grundlage für weiterführende forst- und holzwirtschaftliche produktlinien-Analysen. bundesforschungsanastalt für forst- und holzwirtschaft, Hamburg, Germany. 139 pp.

Silva DAL, Lahr FAR, Garcia RP, Freire FMCS, Ometto AR (2013) Life cycle assessment of medium density particleboard (MDP) produced in Brazil. Int J Life Cycle Ass 2013(18):1404-1411.

Speckels L (2001) Ökologische vergleich verschiedener verwertungs- und entsorgungswege für altholz, dissertation im fachbereich biologie, ordinariat für holztechnologie, Universität Hamburg. Ordinariat für Holztechnologie, Universität Hamburg, Hamburg, Germany. 403 pp.

StELF (2011) Der aktuelle rohholzmarkt in Bayern. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten. www.stmelf.bayern.de/wald/holz/004816/index.php (1 June 2012).

Tsupari E, Monni S, Pipatti R (2005) Non-CO_2 greenhouse gas emissions from boilers and industrial processes. VTT, Espo, Finland. 110 pp.

UBA (2012) Entwicklung der spezifischen des deutschen Strommix 1990-2010 und erste Schätzungen 2011. Umweltbundesamt, Dessau-Rosslau, Germany. 5 pp.

Universiteit Leiden (2010) CML 2001, characterization and normalization data. Universiteit Leiden. Institute of Environmental Science, Faculty of Science, Leiden, The Netherlands. http://cml.leiden.edu/software/data-cmlia.html (19 November 2012).

Wilson JB (2008) Particleboard: A life-cycle inventory of manufacturing panels from resource through product, CORRIM Phase II, Final Report Module F. University of Washington, Seattle, WA. 57 pp.

Wilson JB (2009) Resins: A life-cycle inventory of manufacturing resins used in the wood composites industry, CORRIM: Phase II Final Report, Module H. University of Washington, Seattle, WA.

Wilson JB (2010a) Life-cycle inventory of formaldehyde-based resins used in wood composites in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):125-143.

Wilson JB (2010b) Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):107-124.

Wilson JB (2010c) Life-cycle inventory for particleboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42(CORRIM Special Issue):90-106.

Zeppenfeld G, Grunwald D (2005) Klebstoffe in der holz- und möbelindustrie 2. überarb. DRW Verlag, Leipzig, Germany.

Zimmer B (2010) Ökobilanz waldhackschnitzel. Magazin der Bayerischen Landesanstalt für Wald und Forstwirtschaft und des Zentrums Wald und Forst Weihenstephan 74:22-25.