Appendix A

Table A.1. The share of recovered fibres (re-utilization rate) and virgin fibres (i.e. wood chips from roundwood and sawmill co-products) in paper and particleboard production in three wood utilization scenarios.

Products	Type of pulp	Share in total paper production %	Share of recovered fibres (re-utilization rate) (%)			Share of virgin fibre from roundwood (%)[c]			Share of virgin fibre from sawmill co-products (%)[c]		
			S0	S1	S2	S0	S1	S2	S0	S1	S2
Newsprint	Mechanical	10%	0%	93%	95%	90%	6%	4%	10%	1%	1%
Other graphic papers[a]	Chemical	36%	0%	11%	11%	-	-	-	-	-	-
Total packaging paperboard[b]	Mechanical	43%	0%	75%	95%	90%	20%	4%	10%	5%	1%
Sanitary papers	Chemical	7%	0%	50%	80%	90%	40%	15%	10%	10%	5%
Other papers[a]	Chemical	4%	0%	39%	39%	-	-	-	-	-	-
Total paper and board		100%	0%	51%	61%	90%	39%	29%	10%	10%	10%
Particleboard			0%	27%	42%	70%	45%	33%	30%	28%	25%

[a]Assumed re-utilization rate remains the same in S1 and S2 (GHG emissions reduction is not calculated in the study); [b] includes greyboards, folding boxboard and corrugated board; [c] based on the global wood flows data developed by Bais et al. (2015).

In this study, the type of pulp used for the production of different paper grades (**Table A.1**) was based on the study of Laurijssen et al. (2010). Newsprint paper can be produced from both primary and secondary fibres; the primary fibre is mostly dominated by mechanical pulp. High quality printing and writing paper (other graphic papers category) requires primary fibre which is dominated by chemical pulping, because it requires a high level of brightness and strength. Sanitary papers (e.g. facial tissues, kitchen towels, hand towels and industrial wipes) can be produced from primary fibre or recovered fibre; the primary fibre is generally from chemical pulp because it needs to be strong, absorbent and soft. Packaging paperboard like corrugated board and greyboard could be produced from 100% recovered fibre and folding boxboard from recovered and mechanical fibres. In S0, we assumed that paper and particleboard are produced from 100% virgin fibre (**Table A.1**). In S1, the utilization rate of post-consumer paper and wood in 2010 for the production of paper and particleboard has been applied, taken from CEPI (2011) and Mantau (2012). In Scenario S2, we assumed that the share of recovered pulp in other graphic papers (e.g. printing and writing papers) and other papers remain the same (as S1). For the production of printing and writing papers often no recovered fibre are used (Laurijssen et al. 2010). In S2, we assumed that the recovery rate of post-consumer paper for material use increased from 33 to 39 MtC/year (**see Table 1**). The additional post-consumer paper waste (6 MtC/year) recovered in S2 has been assumed distributed for the production of newsprint (2%), packaging paperboard (79%) and sanitary paper (19%). The average utilization rate of post-consumer paper for newsprint production in S2 increased from 93% (in 2010) to 95% (newsprint average utilization rate in 2015; CEPI, 2015). The average utilization rate of recovered waste paper in packaging paperboard production increased from 75% (in 2010) to 95%. The utilization of post-consumer paper (mixed paper waste) for sanitary paper production increased from 50% to 80%.

Table A.2. Functional unit used to assessed GHG emission reduction in different sectors

Sector/LC Stage	Functional unit
Wood sector	
-particleboard production	kgCO_2-eq/t waste wood used
-paper production	kgCO_2-eq/t waste paper used
Energy sector -waste incineration/combustion	kgCO_2-eq/t waste wood or paper combusted or incinerated
Waste sector -landfill disposal	kgCO_2-eq/t waste wood or paper disposed of in landfill

Table A.3. Life cycle inventory data for different LC stages

LC stage/process	Type of raw material	Type of fuel use	Amount	Unit	Source
Virgin fiber production and extraction process					
Forest operation	Roundwood	Diesel/gasoline Lubricants	100.65 8.09	MJ/m^3 rwe (u.b.) MJ/m^3 rwe (u.b.)	Dias and Arroja, 2012; Gonzalez-Garcia et al., 2009a,b
Sawmill process					
Debarking	Roundwood	electricity	40.40	MJ_e/m^3 rwe	Saravia-Cortez, et al., 2013
Sawing	Mass allocation: Lumber 53% Sawdust 10% Chips 37%	Electricity Diesel Gasoline	39.096 0.8856 0.0166	kWh/m^3 lumber L/m^3 lumber L/m^3 lumber	Puettmann et al., 2013
Recovered fiber recovery process					
Collection					
Full service/kerbside (recovered paper)		Diesel	79.2 - 237.6	MJ/t waste (wet wt.)	Larsen et al., 2009
Drop-off container (recovered paper)		Diesel	133.2 - 176.4	MJ/t waste (wet wt.)	Larsen et al., 2009
Forklift & lorry (recovered wood)		Diesel	6.31	$kgCO_{2-eq}$/t waste (wet wt.)	Eisted et al., 2009
Transfer					
Recovered paper		Diesel	111.24	MJ/t waste (wet wt.)	WRAP, 2011
Recovered wood		Diesel	230.40	MJ/t waste (wet wt.)	
Paper manufacturing process					
Debarking	Roundwood	electricity	40.40	MJ/m^3 rwe	Saravia-Cortez, et al., 2013
Chipping	Roundwood Sawmill co-product	Electricity	542.46 47.41	MJ/m^3 rwe MJ/m^3 rwe	Saravia-Cortez et al., 2013
Pulping	Virgin wood (mechanical pulping)	Electricity Steam	2,200.00 0.00*(1)	kWh/t paper GJ/t paper	Laurijssen et al., 2010
	Virgin wood (chemical pulping)	Electricity Steam	700.00*(2) 22.20*(3)	kWh/t paper GJ/t paper	Laurijssen et al., 2010
	Recovered paper	Electricity Steam	85-500*(4) 0,02-0,60*(5)	kWh/t paper GJ/t paper	Laurijssen et al., 2010
Particleboard manufacturing process					
Debarking	Roundwood	electricity	40.40	MJ_e/m^3 rwe	Saravia-Cortez, et al., 2013
Chipping	Roundwood Sawmill co-product	Electricity	542.46 47.41	MJ_e/m^3 rwe MJ/m^3 rwe	Saravia-Cortez et al., 2013
	Recovered wood		59.24	MJ_e/m^3 rwe	Saravia-Cortez et al., 2013
Drying	Virgin woodchips Recovered woodchips	Heavy fuel oil (0.12 kg HFO/ kg water)	3474.90 823.28	MJ/m^3 PB MJ/m^3 PB	Merrild and Christensen et al., 2009

Table A.3. Continued

LC stage/process	Type of raw material	Type of fuel use	Amount	Unit	Source
Transport					
From forest landing to mills					
By road (share 80%) 40-60t lorry 25-40t capacity Load factor: 50-57% Ave. distance: 150km	Virgin wood MC = 40%	Diesel	2.26 0.35-0.45 0.60-0.62	MJ/m^3 rwe (u.b.)/km L/km (empty) L/km (full)	Gonzalez-Garcia et al., 2009a,b; Schweinle, 2000; Wegner, 1994; Le Net et al., 2011
By rail (share 18%) Ave. distance:400km Wagon number: 20 Load/wagon: 35t Load factor: 50%	Virgin wood	Diesel	0.11	MJ/ MJ/m^3 rwe (u.b.)/km	Gonzalez-Garcia et al., 2009b; Le Net et al., 2011 (for average transport distance)
By ship (share 2%) Load: 3200 m^3 Load factor 50% Distance: 368 nmi-55% 414 nmi-45%	Virgin wood MC = 50%	Diesel	0.31	MJ/ m^3 rwe (u.b.)/nmi	Gonzalez-Garcia et al., 2009b
From collection site to material recovery facility (MRF)					
16t lorry Distance: 20 km	Recovered paper/wood MC = 20%	Diesel	3.84	MJ/t waste (w.w.)/km	Spielmann and Scholz, 2004; Eisted et al., 2009
From MRF or recovered paper/wood dealer to mills/incineration plants/landfill disposal areas					
32t lorry Distance[(6)]: 350 km	Recovered paper/wood MC = 20%	Diesel	1.64	MJ/t waste (w.w.)/km	Spielmann and Scholz, 2004; CCB and FEFCO, 2015
Landfill					
Conventional landfill with flares (S0)					
Indirect: upstream -soil excavation works -on-site daily operations -linear material -provision of gravel -provision of electricity	Recovered paper and wood -30% MC	diesel diesel HDPE gravel electricity	0.5 -1 1 - 3 0.5 - 1.5 80 - 120 5 - 8	L/t waste L/t waste kg/t waste kg/t waste kWh/t	Manfredi et al., 2009
Direct: waste management -on-site operations -use of electricity -CH_4 dispersive -CH_4 flares -CO_2 biogenic dispersive -CO_2 biogenic flares -C left	Recovered paper and wood -30% MC	diesel electricity	1 - 3 5 - 8 11 - 47 1- 4 89-299 326 – 613 178 - 204	L/t waste kWh/t waste kg/t waste kg/t waste kg/t waste kg/t waste kg/t waste	Manfredi et al., 2009 and own calculation
Other parameters: Oxidation efficiency: 40-60%; Emission of landfill gas: 0.5; Emission of leachate: 0.02 Average collection efficiency:50-80%; Methane to CO_2 (biogenic) oxidation efficiency: 95-99% Biogenic C content: recovered (post-consumer) wood = 400-450 kg/t waste; post-consumer paper = 300-440 kg/t waste					

Table A.3 Continued

LC stage/process	Type of raw material	Type of fuel use	Amount	Unit	Source
Engineered landfill with intensive gas utilization (S1)					
Indirect: upstream	Recovered paper				
-soil excavation works	and wood	diesel	0.5 -1	L/t waste	Manfredi et al.,
-on-site daily operations	-30% MC	diesel	1 - 3	L/t waste	2009
-linear material		HDPE	0.5 - 1.5	kg/t waste	
-provision of gravel		gravel	80 - 120	kg/t waste	
-provision of electricity		electricity	8 - 12	kWh/t	
Direct: waste management					
-on-site operations	Recovered paper	diesel	1 - 3	L/t waste	Manfredi et al.,
-use of electricity	and wood	electricity	5 - 8	kWh/t waste	2009 and own
-CH_4 dispersive	-30% MC	CH_4	11 - 47	kg/t waste	calculation
-CH_4 flares		CH_4	1-4	kg/t waste	
-CO_2 biogenic dispersive		CO_2	89-299	kg/t waste	
-CO_2 biogenic flares		CO_2	326-613	kg/t waste	
-C left		C	178-204	kg/t waste	
Indirect: downstream Electricity produced from LFG utilization		electricity	24 – 566	kWh/t waste	Own calculation based on Manfredi et al., 2009
Other parameters:					
Emission of landfill gas efficiency: $D_{LFG} = 0.51$ (paper); $D_{LFG} = 0.23$ (wood)					
Emission of leachate: $D_{Leachate} = 0.02$					
Average collection efficiency over 100 years: 50-80%					
Power plant gas energy recovery efficiency: 25-35%					
Methane to CO_2 (biogenic) oxidation efficiency: 95-99%					
Oxidation efficiency: 40-60%					
Biogenic C content: recovered (post-consumer) wood = 400-450 kg/t waste; post-consumer paper = 300-440 kg/t waste					

*Energy generated is not yet deducted (1) generated steam = 5.40 GJ/t paper (from bark incineration); (2) generated electricity = 1580 kWh/t paper; (3) generate steam = 22.2GJ/t paper; (4) generated electricity from paper rejects = 36-66 kWh/t paper (1200 kWh/t paper rejects; share of paper rejects per tonne recovered paper is 3-6%, Bajpai, 2015); (5) generate steam from paper sludge = 0.61-1.28 GJ/t paper (4.2 GJ/t waste paper sludge; share of paper sludge per tonne recovered paper is 15-31%, Bajpai, 2015); (6) Average transport distance by truck of recovered paper/wood from dealer/MRF to mills is taken from (CCB and FEFCO, 2015); Conversion factor to convert m^3 swe to tonnes product: 1.54 m^3 swe/t particleboard (PB), 4.50 m^3 swe/t mechanical pulp, 2.50 m^3 swe/t chemical pulp; w.w. is equivalent to wet weight

Table A.4. Lower heating values (LHV's) and CO2 emissions factor for different fossil fuels

Fuel	LHV	Unit	CO_2 emission factor[a]	Unit
Natural gas (4000 km, EU Mix quality)*			67.59	g CO_2-eq/MJ
Gas/Diesel oil*	43.1	MJ/kg (0% water)	87.64	g CO_2-eq/MJ
HFO (heavy fuel oil) for marine transport*	40.5	MJ/kg (0% water)	87.20	g CO_2-eq/MJ
Electricity EU mix MV* [b]			127.65	g CO2-eq/MJ_e
Lubricants*	40.2	MJ/kg (0% water)	947	g CO_2-eq/kg
High density polyethylene (HDPE)[c]			185	g CO_2-eq/kg
Gravel[d]			140	g CO_2-eq/t wet waste

* BIOGRACE, 2011; [a] includes GHG emissions of supply and use (or combustion) of one MJ of fuel; [b]distribution lines medium voltage (1-100 KV) for industrial consumers. The EU forest sector is regarded as a medium scale distributor of power & heating. Large scale distributors, like the power production utilities, are not applicable for our GH inventory; [c] Manfredi et al., 2009;

Table A.5. Conversion factors used in this study

Item	Conversion factor	Unit	Source
Recovered wood (20% MC)	847	kg/m^3 particleboard	Merrild and Christensen, 2009
Particleboard density	0.650	t/m^3 particleboard	UNECE/FAO, 2010, p. 21
Recovered paper	1.20	t/t newspaper (dry basis)	Bajpai, 2015
	1.40	t/t sanitary paper (dry basis)	Bajpai, 2015
	1.07	t/t paperboard	Bajpai, 2015
	1.28	t/t paper	UNECE/FAO, 2010, p. 23
Roundwood - particleboard	1.50	m^3 swe/m^3 particleboard	UNECE/FAO, 2010, p. 21
	1.54	m^3 swe/m^3 particleboard	UNECE/FAO, 2010, p. 21
Roundwood - paper	2.87	m^3 swe/t newsprint	UNECE/FAO, 2010, p. 23
	4.35	m^3 swe/t sanitary paper	UNECE/FAO, 2010, p. 23
	3.63	m^3 swe/t paperboard	UNECE/FAO, 2010, p. 23
Roundwood - pulp	4.50	m^3 swe/t chemical pulp	UNECE/FAO, 2010, p. 23
	2.50	m^3 swe/t mechanical pulp	UNECE/FAO, 2010, p. 23

Table A.6. GHG emission reduction per 1% increase of recovered fibre material input per tonne of wood product produced (in kgCO_2-eq/tonne product) in EU-28 and other countries.

Wood products	High estimate (EU-28)	This study (EU-28)	Low estimate (EU-28)	Sikkema et al., 2013* (Canada)	Other sources
Particleboard	5.80	3.01	0.70	1.69 - 6.77	4.00[(1)]
Paper					
-Newsprint	8.67	5.59	0.48	0.15 – 4.90	14.9[(2)]
-Sanitary paper	17.75	0.82	0.13	-	-
-Packaging paperboard	9.56	6.21	0.59	-	-

*Assumed particleboard density of 650 kg/m^3 (UNECE/FAO, 2010); [(1)] Study in Belgium by Fedustria 2011 as cited by Sikkema et al., 2013; [(2)] Study in Netherlands newsprint sector by Norske Skog Parenco between 1991 and 2010 as cited by Sikkema et al., 2013.

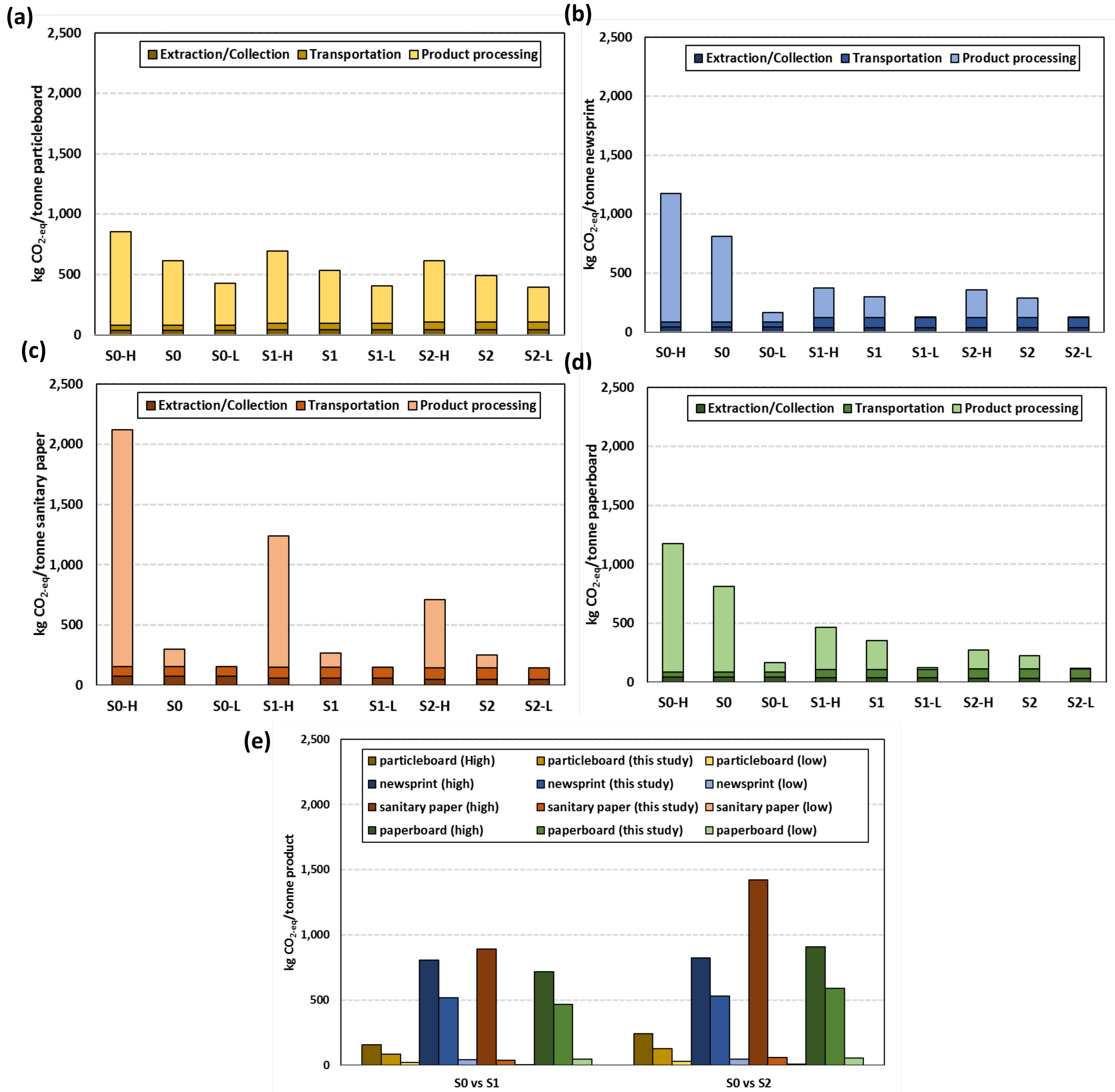

Figure A.1. Estimated GHG emissions by Life Cycle stage (a-d) and GHG emission reductions (e) per tonne of particleboard and paper products in three scenarios: no product cascading (S0); current wood and paper recycling (S1); and optimized product cascading (S2) showing high (-H) and low (-L) estimates.

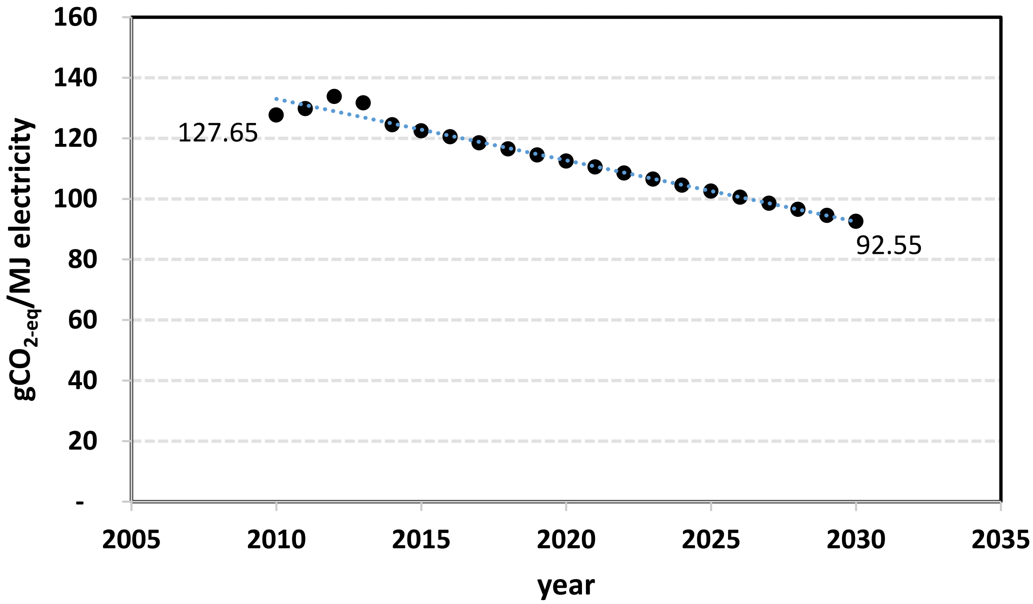

Figure A.2. Trend of GHG emissions per kWh of electricity EU mix from 2010 to 2030 (2014-2030 derived from linear regression in Excel based on electricity EU mix data in 1990 to 2013 taken from European Environment Agency, 2015) . The electricity EU mix is set on 460 g Co_2–eq/kWh in 2010 (source: BioGrace, 2011).

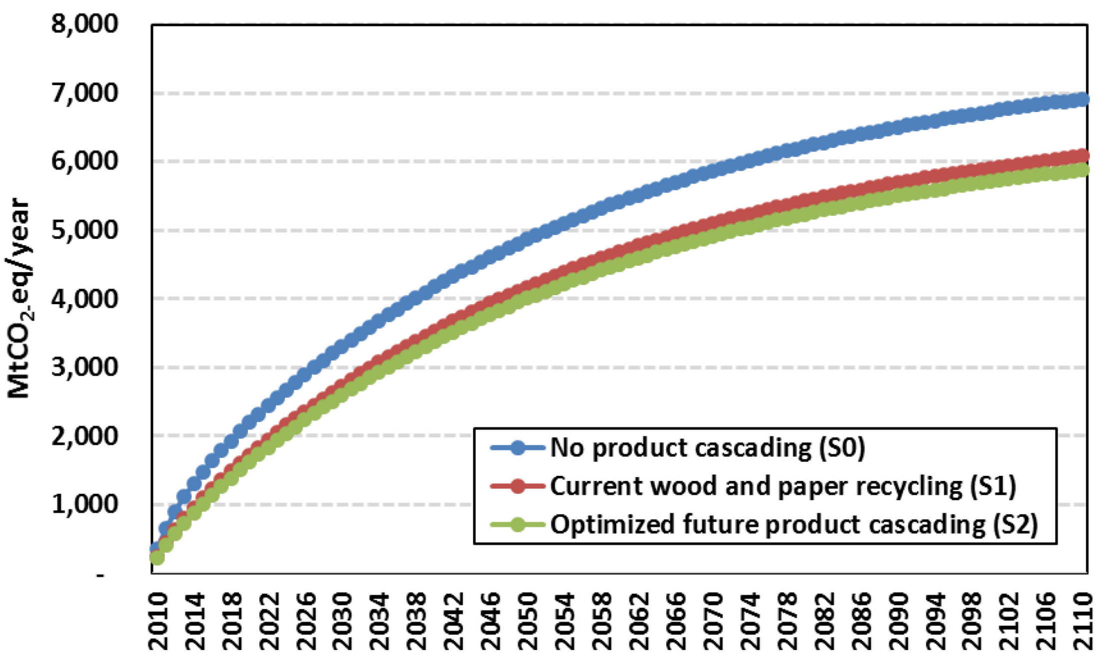

Figure A.3. Annual carbon uptake (from fresh fibres) in harvested wood products over 100 years in three scenarios: no product cascading (S0); current wood and paper recycling (S1); and optimized future product cascading (S2)

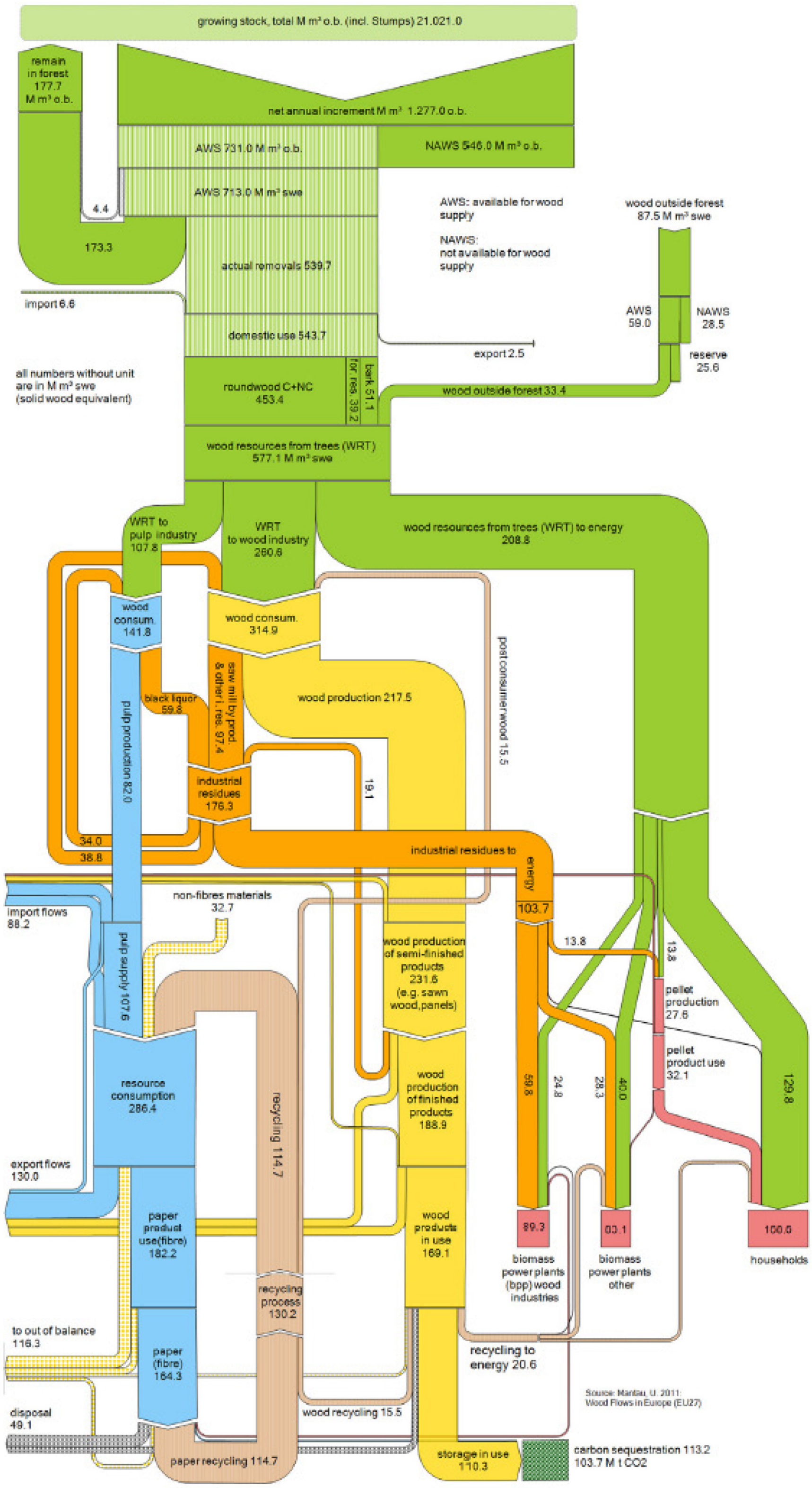

Figure A.4. Wood flows in Europe EU-27 2010 (Mantau, 2015)

References

Bajpai, P. 2015. Management of pulp and paper mill waste. Springer International Publishing, Switzerland.

BIOGRACE, 2011. Condensed list of standard values, version 4-Public. http:// www.biograce.net/content/ghgcalculationtools/standardvalues (accessed 29.09.15)

CCB and FEFCO, 2015. European database for corrugated board Life Cycle studies 2015. CEPI container board (CCB) and European Federation of Corrugated board Manufacturers (FEFCO). http://www.fefco.org/sites/default/files/lca-report-2015.pdf (accessed 14.01.16)

CEPI, 2011. CEPI Key Statistics 2010. European Pulp and Paper Industry. Confederation of European Paper Industries, Brussels, Belgium. http://www.cepi.org/system/ files/public/documents/publications/statistics/2010%20Key%20Statistics%20FINAL.pdf (accessed 29.09.15)

CEPI, 2015. CEPI Key Statistics 2014. http://www.cepi.org/system/files/public/documents/ publications/statistics/2015/Key%20Statistics%202014%20FINAL.pdf (accessed 15.01.16).

Dias, A.C., and Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 37, 368-376.

Eisted, R., Larsen, W.A., Christensen, T.H., 2009. Collection, transfer and transport of waste: accounting of greenhouse gases and global warming contribution. Waste Manage. Res. 27, 738-745.

European Environment Agency (EEA), 2015. Overview of electricity production and use in Europe. http://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment (accessed 11.10.16)

Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009a. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. Int. J. Life Cycle Ass. 14 (4), 340-353.

Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009b. Comparative environmental assessment of wood transport models: A case study of Swedish pulp mill. Sci. Total Environ. 407, 3530-3539.

Larsen, A.W., Vrgoc, M., Christensen, T.H., Lieberknecht, P., 2009. Diesel consumption in waste collection and transport and its environmental significance. Waste Manage. Res. 00, 1-8.

Laurijssen, J., Marsidi, M., Westenbroek, A., Worrell, E., Faaij, A., 2010. Paper and biomass for energy? The impact of paper recycling on energy and CO2 emissions. Resour. Conserv. Recy. 54, 1208-1218.

Le Net, E., Bajric, F., Vötter, D., Berg, S., Anderson, G., Roux, S., 2011. Identification of existing transport methods and alternative methods or new approaches with data about costs, labour input and energy consumption. EFI Technical Report 76, 2011. http://www.efi.int/ files/attachments/ publications/eforwood/efi_tr_76.pdf (accessed 25.01.16)

Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Manage. Res. 27, 825–836.

Mantau, 2015. Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. Biomass Bioenerg. 79, 28-38.

Mantau U., 2012. Woodflows in Europe (EU 27). Project report. Celle, Germany, 24 pp. http://www.cepi.org/system/files/public/documents/publications/forest/2012/CEPIWoodFlowsinEurope2012.pdf (accessed 30.09.2015)

Merrild, H. and Christensen, T.H., 2009. Recycling of wood for particle board production: accounting of greenhouse gases and global warming contributions. Waste Manage. Res. 27, 781-788.

Puettmann, M., Oneil, El., Bergman, R., 2013. Cradle to gate life cycle assessment of softwood lumber production from the Northeast-North Central. Consortium on Research for Renewable Industrial Materials (CORRIM) technical report, April 2013, United States. http://www.corrim.org/pubs/reports/2013/phase1_updates/NENC%20Lumber%20LCA%20final%20May%202013.pdf (accessed 01.10.15)

Saravia-Cortez, A.M., Herva, M., García-Diéguez, Roca, E., 2013. Assessing environmental sustainability of particleboard production process by ecological footprint. J. Clean. Prod. 52, 301-308.

Schweinle, J. 2000. Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterführende forst- und holzwirtschaftliche Produktlinien – Analysen [Analysis and evaluation of forest production as a base for forest products], 2nd edition. Wiedebusch, Hamburg.

Sikkema, R., Junginger, M., McFarlane, Faaij, A., 2013. The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy – A case study on available forest resources in Canada. Environ. Sci. Policy 31, 96-108.

Spielmann, M. and Scholz, R.W., 2004. Life cycle inventories of transport services – background data for freight transport, The EcoInvent Database. Int. J. Life Cycle Ass. 10, 85-94.

UNECE/FAO, 2010. Forest Products Conversion Factors for the UNECE Region, Geneva Timber and Forest Discussion Paper 49. United Nations, Geneva. https://www.unece.org/fileadmin/DAM/timber/publications/DP-49.pdf (accessed 15.09.14)

Wegner, G., 1994. Der positive Beitrag der Holznutzung zur CO2 Bilanz. S. 187-197. In: Bröker, F.W. (Ed.) Kongressforum „Holz“ im Rahmen der Internationalen Grünen Woche, [Positive contribution by timber to CO2 balance], Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, April 1994, Nr. 176, Max Wiedebusch. Berlin: Kommissionsverlag Buchhandlung.

WRAP, 2011. Kerbside Collections options: Wales. Main report. Wales, UK. p.187. http://www.wrapcymru.org.uk/sites/files/wrap/Kerbside%20Collections.pdf (accessed 15.10.15)