Literature Review – End of Life Carbon Accounting for Wood Composite Panels

For

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1 Introduction

Producing all materials, renewable and non-renewable, has environmental impacts. Over the years, assessment of environmental burdens has evolved from not just considering site-specific impacts but to now include impacts of specific product manufacturing, use, and end of life options. Historically, a preferred environmental building product was one that was made from renewable or recycled resources. Today, building materials are held to a higher standard of transparency that goes beyond their natural attributes. Builders, designers, politicians, and the general public are asking for the full suite of a material's environmental impact to meet "green building" standards as well as state and national emission reduction benchmarks, just to name a few. Building materials that have low embodied carbon and energy are sought out, and other functional aspects such as structural performance, ease of installation and product durability are also desired. Users of building materials are increasingly relying on science-based attributional life cycle assessment (LCAs) studies that offer assurance that the material has the environmental attributes they seek.

LCAs will become increasingly more important as they are used by all industries to inform product and process design, as well as building system development, as builders seek to minimize energy consumption and carbon releases. Going forward, the need for credible, scientific, and impartial LCA-based information will be greater than ever. One cannot assume wood products will continue to enjoy environmental superiority without continued advancement in environmental and product performance, from cradle to grave.

The biogenic carbon which is stored in wood products during their useful life may be emitted to the atmosphere at their end of life (EoL) such as by incineration or by landfilling through leaching and carbon dioxide (CO_2) and methane (CH_4) emissions. The rate of which carbon is released is highly dependent upon the EoL treatment (García and Freire, 2014; Wang, Wang and Yang, 2018; Lao and Chang, 2023). Landfilling is considered a carbon-locking, where it can permanently store carbon (88%)(US-EPA, 2020a). This is due to the type of landfilling method used for wood, e.g., compact the wood and seal the landfill to prevent water and oxygen from entering the system preventing anaerobic decomposition. Therefore, there is growing interest in the development of waste-specific decay factors for estimation of greenhouse gas emissions (GHG) from landfills and incineration (Wang *et al.*, 2011; Ximenes *et al.*, 2018; Ximenes, Cowie and Barlaz, 2018). Recycle and reuse of wood products after their initial service life is preferable, but in most cases wood products, particularly wood composites panels (WCP) end up in the landfill or used for energy recovery (Ximenes, Cowie and Barlaz, 2018).

Wood composite panels are well known for their environmentally friendly attributes of being sustainable, renewable, biodegradable, and predominantly made from wood residues generated during lumber and plywood production (Puettmann and Salazar, 2018a, 2018b; Puettmann, 2022). This paper focuses on EoL life carbon impacts of WCPs obtained from published papers with a focus on the different biogenic carbon EoL methodologies published, biogenic carbon emission factors for WCP, and carbon remaining and stored in WCP in landfills.

1.1 Carbon in Wood Composite Panels

When round-shaped logs are processed into rectangular boards at sawmills, coproducts in the form of bark, hogged fuel, sawdust, shavings, and chips are generated. These coproducts may be used for heat energy onsite at the facilities, used in pulp and paper production, or in the manufacturing of wood

composite panels (WCPs). WCPs represent 3.2 percent of the total harvested wood volume in the United States (Oswalt *et al.*, 2019). In 2016, wood processing facilities in the United States generated 58 million mt (dry) of residues (Oswalt *et al.*, 2019). These residues were primarily used for fuel (46%) and fiber products (38%) including WCPs.

In 2019, there was an estimated 291 million cubic meters (m^3) of WCPs in use in North America that corresponds to a carbon pool of 354 million metric tons of carbon dioxide equivalents (Puettmann, 2022). This WCP carbon pool is enough to offset 24 years of cradle-to-gate cumulative carbon emissions (fossil and biogenic sources) emitted during production of these panels (Puettmann, Bergman and Oneil, 2016; Puettmann and Salazar, 2018a, 2018b; Puettmann, 2022). In other words, producing and using WCPs stores carbon for long periods because the amount of carbon emitted during the production of the panels is far less than what the panels themselves are capable of storing over their lifetime of product use.

The largest consumer of solid wood products in the United States is the construction sector. New housing construction represented approximately one-third of all solid wood products manufactured and imported into the United States in 2019. Residential repairs and remodels consume an equivalent amount (one-third) of solid wood products as new house construction (Figure 1). In 2019, furniture manufacturing used 36 percent of the total wood products consumed in the manufacturing sector using 6.75 million m^3 of lumber and wood panels (Brandeis *et al.*, 2021).

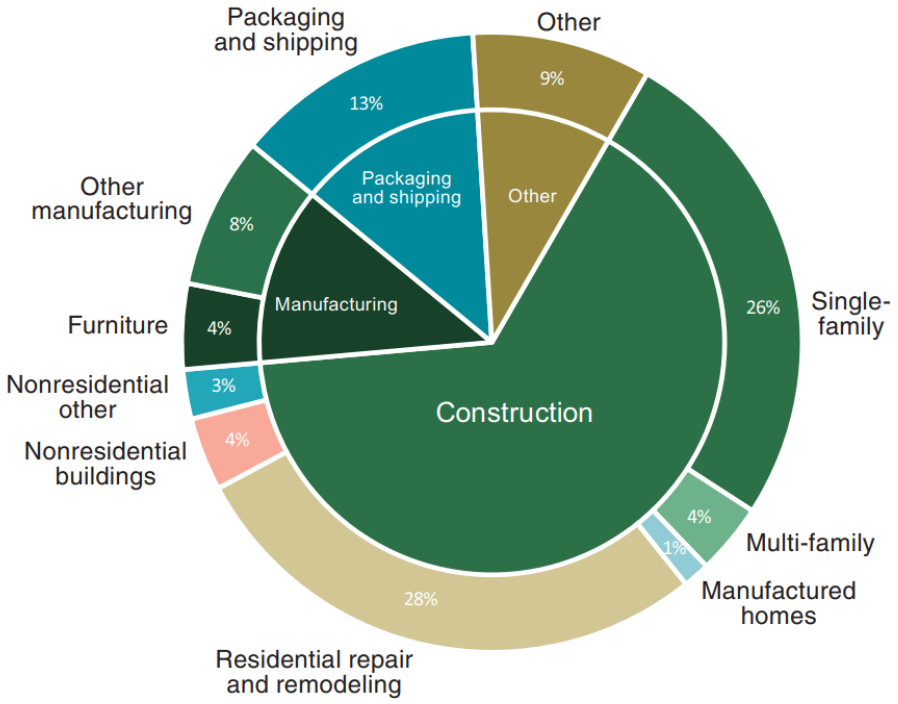


Figure 1 Solid wood products consumption by end use market, 2019. Source: (Brandeis et al., 2021)

1.2 Wood Product Life Expectancy

It is globally understood that wood products store carbon for long periods of time in buildings and play a significant role in carbon mitigation(O'Connor, 2004; UNECE, 2009; Lippke *et al.*, 2010; Geng *et al.*, 2017; Kazulis *et al.*, 2017; Johnston and Radeloff, 2019; Prestemon, Nepal and Sahoo, 2022). WCPs, including particleboard, medium density fiberboard (MDF), and hardboard–engineered wood siding and trim (EWST) can represent close to 10% of the total wood by volume that is used in light frame construction (McKeever and Phelps, 1994). This does not consider other uses for WCP such as cabinets, furniture, and flooring which are anticipated to have an average service life of 25–100 years (NACHI, 2023). According to IPCC guidelines (IPCC, 2019), the estimated service life of engineered wood products is 30.5 years.

Using wood products over alternative building materials provides the greatest carbon benefit (Lippke *et al.*, 2010, 2021) . A typical building in North America has an average service life of 80 years (O'Connor, 2004), although service lives could be extended to 100+ years. Decay and insect damage remain the greatest challenges for many regions in North America. The International Association of Certified Home Inspectors (IACHI) has published estimated life expectancies of homes including structural and nonstructural wood components (NACHI, 2023).

Table 1 Production of value added downstream product categories production and expected service life (CPA, 2021; NACHI, 2023)**.**

Down Stream end use for particleboard and medium density fiberboard combined (CPA, 2021)	**Production, 2021 (MSF ¾" basis)**	**Percent of production**	**Expected service life (yr.) (NACHI.org)** (NACHI, 2023)
Shelving, Siding & Paneling	140,498	2%	50+
Office Furniture	245,651	4%	10-50
Retail/Store Fixtures	250,659	4%	50+
Door Components	373,033	7%	100+
Household Furniture	470,137	8%	10-50
Moulding & Millwork	478,411	8%	100+
Flooring	478,726	8%	25+
Cabinets, Vanities & Countertops	1,363,409	24%	20-50+
Other, Not Classified	1,836,891	33%	estimate 50

Particleboard and MDF (Hafezi *et al.*, 2021) have a life expectancy of 60 years. In contrast, when these products are used as a flooring underlayment and exposed to moisture, their service life is only 25 years. Cabinets and shelving ranged from 50-100 years, while entertainment furniture was only 10 years. It is difficult to assess the actual service life of many uses that WCP provide, estimates of which are outlined in Table 1. If we align the products using the service life reported by the NACHI and assume no change in downstream product use over the service life of the product, about 15% of the panels produced in 2021 will be in service 50 years later, leaving the remaining 85% assumed to be landfilled or incinerated.

1.3 Life cycle assessments on WCP– Cradle to grave

Internationally, there are a plethora of LCAs on WCP with the majority having a system boundary encompassing cradle to gate (Kouchaki-Penchah *et al.*, 2016; Puettmann, Bergman and Oneil, 2016; Erdil, Yilgor and Gungor, 2017; Hussain, Malik and Taylor, 2017; Puettmann and Salazar, 2018a, 2018b;

Gonzalez-Garcia *et al.*, 2019; Erdil and Yilgor, 2020) . A few have included cradle to grave using two EoL scenarios of landfilling and incineration with nearly all indicating that landfilling may be preferrable from a carbon emission standpoint (García and Freire, 2014; Wang, Wang and Yang, 2018; Hafezi *et al.*, 2021; Lao and Chang, 2023). Wood products that end up in landfills represent 6.2% of all municipal solid waste in 2018, when no other options are available, such as, energy recovery and reuse (US-EPA, 2020a).

1.4 Determining Carbon Emissions at End of Life

Wood is among the major contributors to biogenic carbon in landfills and is estimated to represent 6.2% of the total municipal solid waste in the U.S. (US-EPA, 2020a) and 7.1% of the construction and demolition waste(US-EPA, 2018). In Australia, it is reported that particleboard and MDF account for 80% of the total volume of engineered wood products (EWPs) consumed (Ximenes, Cowie and Barlaz, 2018). A substantial amount of EWPs (approximately 32% of the total volume of wood waste) disposed of in landfills annually (Ximenes *et al.*, 2018).

Although engineered wood products (EWPs) and paper represent a substantial component of the solid waste stream (Table 2), there is limited information available on their carbon dynamics in landfills (Wang *et al.*, 2011, 2013; O'Dwyer, Walshe and Byrne, 2018; Ximenes *et al.*, 2018). Several studies have looked to help assess carbon emissions from EWP in landfills both in the United States (Wang, Wang and Yang, 2018) and worldwide (Ximenes, Cowie and Barlaz, 2018). While most studies reported both solid wood (hardwoods and softwoods) (O'Dwyer, Walshe and Byrne, 2018), only one of them included EWP which include plywood, oriented strandboard, particleboard, and medium density fiberboard.

This section will review carbon emissions reported by using life cycle assessment and by various end of life methodologies, as well as laboratory determined emission factors or DOC_f (degradable organic carbon)-dissimilated or degraded organic carbon for wood products under anaerobic conditions. It should be noted that the later, DOC_f, are used in national inventory reporting, such as Waste Reduction Model (WARM) (US-EPA, 2020b). DOC_f is defined as the fraction of the degradable organic carbon in a biomass that decomposes in the environment under aerobic and anerobic conditions. Decomposition rate of the organic matter under aerobic condition is about 3-4 times higher than that under anaerobic condition in a managed landfill (IPCC, 2019).

Table 2 Estimated carbon storage from forest products deposited in US landfills. Extracted from Wang et al. (2011)

Municipal Solid waste	Fraction of each category (%)[a]	Discarded in Landfills (Tg)[b]	Moisture content[c] (%) wet basis	Carbon storage[d] (Tg)
Residential		**133.0**		
Lumber	2.1	2.8	11.3	1.1
Plywood	0.8	1.1	9.0	0.4
OSB	0.3	0.4	7.8	0.2
MDF and PB	0.4	0.5	7.2	0.2
Commercial		**108.8**		
Lumber	4.1	4.5	11.3	1.7
Plywood	0.6	0.7	9.0	0.3
OSB	0.6	0.7	7.8	0.3
MDF and PB	0.4	0.4	7.2	0.2
C & D Waste		**61.2**		
Lumber	15.1	9.2	11.3	3.5
Plywood	4.3	2.6	9.0	1.1
OSB	4.7	2.9	7.8	1.2
MDF and PB	0.8	0.5	7.2	0.2
TOTAL		**241.9**		**10.3**

[a] The percentage of lumber, PW, OSB, MDF and PB in residential, commercial, and C&D waste was adapted from a waste characterization study for Delaware.

[b] The total MSW landfilled in 2006. it was assumed that 55% and 45% of MSW landfilled originated from residential and commercial sources, respectively. The wet weight of lumber, PW, OSB, MDF, and PB was computed by multiplying the wet weight of the specific waste stream by the corresponding percentage.

[c] The moisture content of lumber was the average of measurements on untreated and treated lumber.

[d] Carbon storage was estimated by multiplying the CSFs by the dry mass of each wood. The average of the CSFs of HWs and SWs was used for lumber (0.43 g C dry/g wood); while the average of MDF and PB (0.38 g C/dry g wood) was used for the mixture of MDF and PB.

1.4.1 LCA Methods

The biogenic carbon stored in wood products when they enter a landfill can be significant, therefore the assumptions around disposal and methods to determine carbon emissions can be significant (Wang *et al.*, 2011; Wang, Wang and Yang, 2018; Ximenes, Cowie and Barlaz, 2018) The differences in assumptions and methodologies could cause confusion, potentially hindering acceptance of any one method. The goals of these methodologies differ (Table 2) in how they account for carbon emissions and storage over a product's life span, which influence the net carbon emissions or storage results. The PAS 2050 (BSI, 2011) and ISO 14067 (ISO, 2018) methods goals are to initiate a uniform methodology for calculating cradle to grave carbon emissions. While the GHG Protocol method provides guidelines on carbon accounting and reporting(Wang, Wang and Yang, 2018).

Publicly Available Specification (PAS) 2050 - *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* was developed by the British Standards Institution in 2008(BSI, 2011). PAS 2050 is the first consensus-based and internationally applicable standard on product carbon foot printing that has been used as the basis for the development of other standards internationally. The 2011 revision to PAS 2050 was developed through extensive consultation with international

stakeholders, and in particular, through significant engagement with the wide PAS 2050 user community. The Greenhouse Gas Protocol was released in 2011, provides in not only requirements for GHG inventories of products but also requirements for reporting. Both these standards consistent in their methods, while their standard development process has led to different standards.

ISO 14067 defines the principles, requirements, and guidelines for the quantification of the carbon footprint of products (ISO, 2018). The aim of this document is to quantify GHG emissions associated with the life cycle stages of a product, beginning with resource extraction and raw material sourcing, and extending through the production, use and end-of-life stages of the product.

Carbon storage is expressed as carbon dioxide equivalents (CO_2e) and usually deducted from the total embodied carbon and reported as a net carbon emission (Wang, Wang and Yang, 2018). All methods allow the carbon stored in wood products to be reported as a negative (deduction) emission (Figure 2). The ISO 14067 method allows the reporting of carbon storage (as a deduction), but it must be reported separately and not included in carbon emissions (CF in figure 2) result (Table 2).

Only the PAS 2050 method provides guidance on calculating delayed emissions (Wang, Wang and Yang, 2018). Figure 3 shows the cradle to grave PAS 2050 as reported by Wang et al. (2018). As mentioned earlier, the assumptions derived around EoL can be significant to the overall carbon impact of product. When wood products are incinerated at the EoL, the biogenic carbon emissions are immediately emitted into the air as Wang et al. (2018) shows in Figure 3 under Scenario 2. When the incineration of wood is captured for energy, the energy value can be used as a displacement value for fossil fuels and provide a carbon displacement benefit (Lippke *et al.*, 2021) in the cradle to grave analysis of a wood product.

WCP have long service lives, therefore, the effect of delayed emissions of carbon storage may be important to carbon emissions calculations. Only the PAS 2050 methodologies apply a dual approach to calculate carbon storage by focusing on the effect of delaying an emission on the radiative force within the 100-year assessment period (Wang, Wang and Yang, 2018). The “dual approach” as described by Wang et al. (2018) applies to the carbon storage at time 0 and delayed emissions of the carbon storage over the service life of the product. The incineration scenario shows the carbon that is stored in the wood product is released after the service life, that is, the time of carbon storage is the same as that of the product service life. The carbon is released when the wood product is incinerated. In the landfill treatment, 98.9% of the biogenic carbon can potentially be permanently stored, and only 1.1% of carbon is released into the atmosphere (Figure 3).

Table 3 An overview of key aspects specified in carbon footprint protocols: Publicly Available Specification (PAS) 2050, Greenhouse Gas Protocol Product Standard (GHG Protocol), and ISO 14067 Carbon Footprint of Products (ISO 14067). Source: (Wang, Wang and Yang, 2018)

Specification and Requirement		PAS 2050	GHG Protocol	ISO 14067
Goal		To provide a uniform specification for GHG emissions of goods and services	To provide detailed guidelines on accounting and reporting	To standardize the quantification process and the communication of GHG emission
Life cycle stage included		Cradle-to-grave	Cradle-to-grave	Cradle-to-grave
				Cradle-to-gate
				Gate-to-gate
		Cradle-to-gate	Cradle-to-gate	Partial life cycle
Cut-off criteria		Exclusion based on materiality (1<%); at least 95%of the complete product life cycle must be included; no scale-up requirement to account for 100%	No cut-off criteria exist, because 100% completeness is necessary	No specific criteria available
Capital goods		Excluded	Excluded, but encouraged to be included	Excluded if they do not significantly affect the overall conclusion
Biogen carbon	**Carbon storage**	Stored carbon within 100 years shall be recorded and accounted for in the CF calculation	For cradle-to-gate system, credit is given to biogenic carbon storage	If carbon storage is calculated, then it shall be separately reported but not included in the CF result
	Delayed emissions	A weighting factor is included and proposed	Shall[a] not be included	Shall not be included
Other exclusions	Land-use change	Specific procedure and provides default soil emission per country	Provides guidance for determining attributable impact	Direct land-use change shall be separately documented; indirect land -use change should be considered
	Others	Other exclusions include the transport of workers to their workplace and consumers to purchase site, human energy inputs to the process, and animals providing transport services		
Allocation		(1) Avoiding allocation by process subdivision or system boundary expansion (2) Supplementary requirements (3) Economic allocation	(1) Avoiding allocation by process subdivision and redefining the functional unit or system expansion (2) Physical relationships (3) Economic or other allocation methods	
Global warming potential		100 years		
[a]Shall means recommendation.				

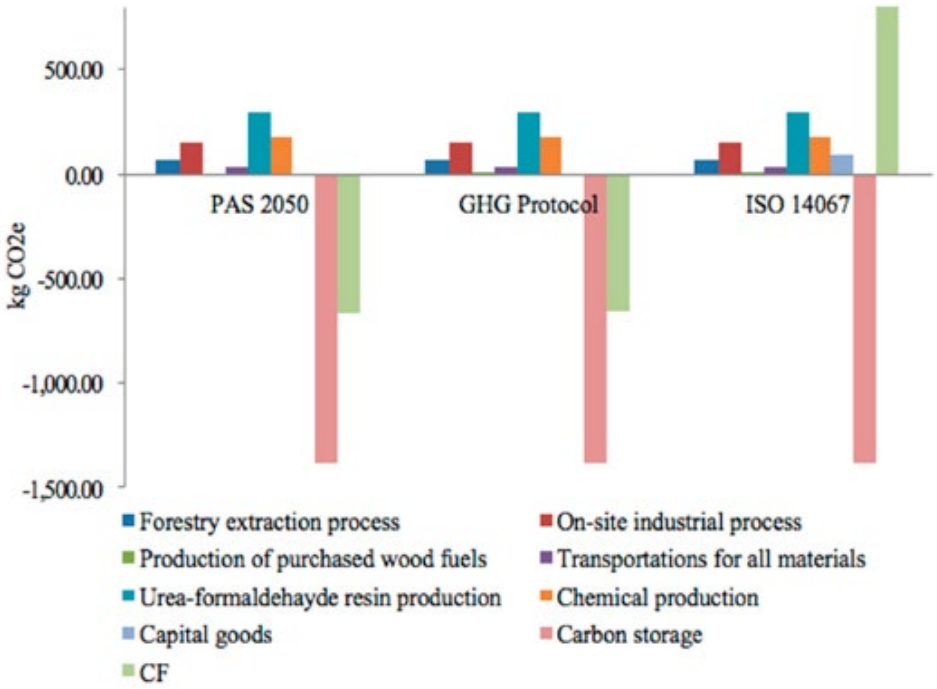


Figure 2 Cradle to gate life cycle carbon footprint of MDF quantified by PAS 2050, GHG protocol, and ISO 14067. Source: (Wang, Wang and Yang, 2018)

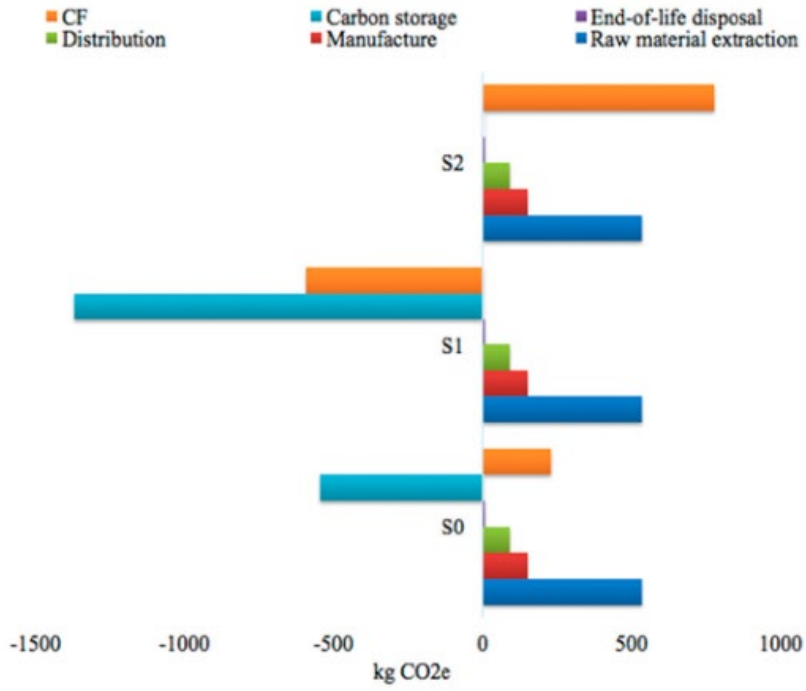


Figure 3: Cradle to grave carbon footprint of MDF quantified with PAS 2050, S0: 40% incineration, 60% landfilled, S1: 100% landfilled, and S2: 100% incineration. Source: (Wang, Wang and Yang, 2018)**.**

1.5 EoL measured carbon emissions from landfills

Anaerobic decomposition of waste in landfills results in methane generation. Methane is produced prior to any gas collection systems making methane capture less than 100 percent. Landfills are estimated to be the second largest source of anthropogenic methane in the U.S. and globally (Wang *et al.*, 2011). Since wood does not decompose in landfills, it has the potential to be a significant source of biogenic carbon storage.

The carbohydrates (cellulose and hemicellulose) are the major biodegradable components of wood while lignin is the other major organic component. The presence of lignin reduces carbohydrate bioavailability, as lignin has long been considered recalcitrant under anaerobic conditions (Wang *et al.*, 2011). Additional factors proposed to influence the anaerobic biodegradability of wood include the proportion of structural and nonstructural carbohydrates, cellulose crystallinity, relative sapwood and heartwood content, and toxic components (Gunaseelan, 1997).

Determining carbon emissions specific to wood decay rates (DOC_f) in landfills specific to wood products as has limited assessment (O'Dwyer, Walshe and Byrne, 2018; Ximenes, Cowie and Barlaz, 2018). Only Ximenes et al. (2018) reported EWP recovered from landfills in Austria where carbon losses were reported for MDF between ~1 – 6 percent and for particleboard around 6 percent depending on the region. The results from this study and those from laboratory test (Wang *et al.*, 2011) indicate a low biodegradability of EWPs (particleboard and MDF) relative to the IPCC default factor (50%) for all organic materials (IPCC, 2019) and the 20% for wood products adopted by the US EPA Warm Model version 15 (US-EPA, 2020b).

In the United States, Wang et al. (2011) reported methane yields and decay rates, as well as carbon storage all under laboratory reactor anaerobic conditions. Methane (CH_4) emissions which have a greenhouse gas factor 35+ times that of carbon dioxide were measured for MDF at 4.6 mL CH_4/g and 5.6 for particleboard (Wang *et al.*, 2011). Similar results were found in Ximenes et al. (2018) for MDF while considerably less for particleboard at 1.6 mL CH_4/g (Table 4). Compared to other EWP and paper, both particleboard and MDF had significantly lower methane yields, indicating a much slower decay rate under these conditions (Table 4).

Table 4 Carbon loss and methane yields for various engineered wood and paper products from both US and Australia wood and paper species.

Product	Carbon loss (%) by mass	Methane yields mL of CH_4/g	Reference	Wood region
Particleboard	1.56	1.6	Ximenes et al. 2018	Australia
Particleboard	1.3	5.6	Wang et al. 2011	US
MDF	0.66	6.6	Ximenes et al. 2018	Australia
MDF	1.1	4.6	Wang et al. 2011	US
OSB	19.9	-0.1	Wang et al. 2011	US
Plywood	1.4	6.3	Wang et al. 2011	US
Solid wood - softwood	1.8	7.5	Wang et al. 2011	US
Cardboard	49.9	155.5	Ximenes et al. 2018	Australia
Copy paper (recycled)	88.3	279.7	Ximenes et al. 2018	Australia

Both studies used laboratory-scale reactors operated under optimal conditions for anaerobic decay. *"The extent of decomposition observed in these reactor studies is unlikely to be achieved and/or sustained in operational landfills and can thus be considered to be an upper limit"* (Ximenes, Cowie and Barlaz, 2018).

Carbon losses were particularly low (0.66-1.56%) for particleboard, MDF, and plywood as reported by both Ximenes et al. (2018a) and Wang et al. (2011) (Table 4) with the exception of OSB where carbon losses were nearly 20 percent. The particleboard and MDF used in Ximenes et al. (2018a) study was comprised of at least 85 percent wood particles and up to 13 percent urea formaldehyde (UF) resin or up to 13 percent melamine urea formaldehyde (MUF) resin, and up to 2 percent paraffin wax. For comparison, the composition of North American particleboard was over 92 percent wood particles, nearly 7 Percent resin (UF, MUF, polymeric methylene diphenyl diisocyanate (PMDI), and phenol formaldehyde (PF)) and less than 0.5 percent wax (CPA, 2018b). MDF was nearly 90 percent wood particles, over 9.5 percent resin (UF, MUF, and pMDI), and over 0.5 percent wax (CPA, 2018a). In summary, Ximenes et al. 2018 and Wang et al. 2011 both used laboratory scale reactors which operate under optimal conditions for anaerobic decay, resulting in decomposition which would unlikely be achieved in operational landfills. These conditions "simulate" maximum methane yields under optimal anaerobic conditions. The methane yields reported in these studies would most likely not be achieved in operational landfills because some aerobic decay would also be present.

2 Take a Ways

- Laboratory anaerobic reactor test underate the methane emissions during the decomposition rate of engineered wood products.
- Carbon losses reported for particleboard and MDF ranged from 0.66 – 1.56 percent in laboratory anaerobic laboratory tests
- Carbon losses reported for particleboard and MDF ranged from 1-6 percent in landfill evacuation in Austria. These losses are within the range of the bench scale tests, and validate, in my mind, the very low carbon losses associated with WCPs.
- Although not discussed above, the conversion of UF resin to methane from particleboard and MDF was insignificant (Ximenes *et al.*, 2018)
- Carbon storage (the amount of carbon that is not converted to methane or carbon dioxide) was 0.38 g of carbon per gram (C/g) (1.39 g CO2/g) of dry wood for particleboard and 0.37 g of C/g (1.36 g CO2/g) of dry wood for MDF (Wang *et al.*, 2011).
- One carbon emissions factor for all wood products and regions may not be appropriate. The major factors that influence carbon emissions from the landfill are climate, landfill type and its management, and product type.
- Municipal waste by value added downstream product categories (furniture, cabinets, flooring etc.) is not available.
- Methodology (PAS 2050, GHG Protocol, and ISO 14067) differences exist for cradle to grave biogenic carbon accounting and reporting.
- One study (Wang, Wang and Yang, 2018) indicated PAS 2050 was the preferred method for assessing cradle to grave MDF as it accounts for the carbon storage in products as a deduction.
- PAS 2050 protocol provides a best opportunity to achieve greenhouse gas reduction targets because credit is given to the carbon storage and the carbon storage is recorded accounted for over a 100 year time frame.
- The GHG protocol also allows credit to the carbon storage, but does allow for the delayed emissions
- ISO 14067 allows for transparent accounting and reporting, therefore is the superior standard for communicating greenhouse gas results. The carbon storage is reported but not allowed as a credit. The method does not allow for delayed emissions.
- Landfilling extends the carbon storage of wood products for centuries
- Incineration releases all the carbon stored over the life span of the product, but when substitution is included, the carbon benefit over fossil emissions can be achieved.

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