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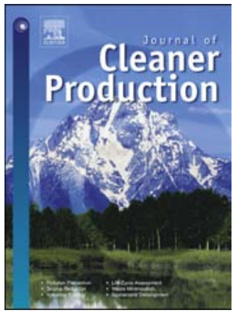

Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration

Rita Garcia, Fausto Freire

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- The influence of methodological issues in the particleboard CF calculation was assessed.
- Biogenic C is addressed differently by the methodologies leading to different CFs.
- Accounting for delayed emissions may reduce the particleboard CF by 80-200%.
- The CF was very sensitive to different accounting of electricity from incineration.
- Capital goods accounted for 12-20% of the particleboard CF and should not be neglected.

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Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration

Rita Garcia[a], Fausto Freire[a,]*

[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Polo II Campus, R. Luís Reis Santos, 3030-788 Coimbra, Portugal

Abstract

This article aims to assess: i) the carbon footprint (CF) of particleboard produced in Portugal, and ii) the influence of different methodological issues in the particleboard CF calculation by comparing four CF methodologies (ISO/TS 14067; GHG Protocol Product Standard; PAS 2050; Climate Declaration). A life-cycle model was developed for particleboard (functional unit: 1 m^3). Both cradle-to-gate and cradle-to-grave (end-of-life scenarios: incineration and landfill) assessments were performed. Six methods to assess delayed emissions were analyzed. The main methodological differences between the CF methodologies are the treatment of biogenic CO_2, multifunctionality, and unit process exclusions (e.g. capital goods). A wide range of CFs was calculated: -939 to 188 kg CO_2 eq/m^3 (cradle-to-gate); 107 to 201 kg CO_2 eq/m^3 (cradle-to-grave; incineration) and -692 to 433 kg CO_2 eq/m^3 (cradle-to-grave; landfill). The inclusion (negative CF) or exclusion (positive CF) of biogenic carbon storage in the reported CF dominated the differences in results and the ranking of end-of-life scenarios strongly depended on that assumption. ISO/TS 14067, the GHG Protocol and PAS 2050 explicitly include both emissions and removals of biogenic CO_2 in the CF calculation. On the other hand, the Climate Declaration does not account for biogenic CO_2 or carbon storage, which may bias the comparison with competing products that do not store biogenic carbon (e.g. fossil-based materials). The CF of particleboard was also very sensitive to the different approaches to deal with multifunctionality in the incineration process by the various CF methodologies. Moreover, although not mandatory, delayed emission accounting significantly affected the results for the incineration scenario. Capital goods accounted for 12-20% of the CF. Future guidelines for wood-based panels, such as Product Category Rules, should, therefore, require that carbon storage is assessed and reported, accounting of waste-to-energy burdens is harmonized and capital goods are included.

Keywords: Biogenic CO_2; carbon storage; delayed emissions; multifunctionality; wood-based panels.

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* Corresponding author. Tel.: +351 239 790 708/39

E-mail addresses: rita.garcia@dem.uc.pt (R. Garcia), fausto.freire@dem.uc.pt (F. Freire).

1. Introduction

Wood-based panels have been gaining increasing importance as an alternative to solid wood in the furniture industry and the construction sector (FAO, 2012). Wood-based panels are produced using processed wood and a synthetic binder and their properties (e.g. size, strength, fire resistance and bio-resistance) can be engineered depending on the expected usage (e.g. structural applications in buildings, or nonstructural applications, such as furniture, interior doors, and decorative paneling). Europe is one of the largest worldwide producers and consumers of wood-based panels. The main types of wood-based panels produced in Europe are particleboard and fiberboard (including medium density fiberboard, high density fiberboard and hardboard).

There are a number of critical issues associated with the life cycle (LC) of wood-based panels, particularly regarding the calculation of the carbon footprint (LC greenhouse gas emissions).Wood-based panels are generally perceived as a potentially carbon-neutral material since they incorporate biogenic carbon. Nevertheless, greenhouse gas (GHG) emissions related to its production, such as those associated with ancillary materials or manufacturing processes, can have a high contribution to the carbon footprint (CF) (Werner and Richter, 2007). Moreover, wood-based panels, in general, have a relatively long service life (more than 10 years), therefore, understanding the dynamics related to storage and delayed carbon emissions in both use and disposal phases is of key importance. There are several approaches to account for temporary storage and delayed emission of biogenic carbon (e.g Fearnside et al., 2000; Moura-Costa and Wilson, 2000; Levasseur et al., 2010, 2012; EC JRC, 2010; Mueller-Wenk and Brandão, 2010; BSI, 2011; Kendall, 2012). However, there is no consensus neither on whether temporary carbon storage should be accounted for nor which is the best approach to assess it (Brandão and Levasseur, 2011; Brandão et al., 2013). Another characteristic of wood production chains is its multifunctionality, which introduces an important methodological question of how to allocate environmental burdens between the different outputs (Jungmeier et al., 2002a).

Several methodological approaches for CF calculation have recently been developed, e.g. the Climate Declaration (IEC, 2008a); BP X30-323 (AFNOR, 2009), PAS 2050 (BSI, 2011); the Japanese CFP Communication Program (JEMAI, 2012); the GHG Protocol Product Standard (WRI and WBCSD, 2011); ISO/TS 14067 (ISO/TS, 2013). Different CF tools adopt different methodological approaches, which can compromise comparisons between products (Draucker et al., 2011; Whittaker et al., 2011; Dias and Arroja, 2012). Because of the methodological challenges associated with the wood-based panel supply chain, understanding how different methodologies treat these issues and how important are those to the results is of key importance for decision makers, companies and LCA researchers and practitioners. Several LC-based studies assessed the environmental impacts of wood-based products (e.g. timber: Cambria and Pierangeli, 2012; Eshun et al., 2012; wooden building products: Werner and Richter, 2007; wood floor coverings: Nebel et al., 2006; paper: Lopes et al., 2003; Dias and Arroja, 2012; paper pulp: González-García, 2009a). Regarding wood-based panels, particleboard was assessed by e.g. Rivela et al. (2006), Wilson (2010a), Saravia-Cortez et al. (2013), Silva et al. (2013); medium density fiberboard by e.g. Rivela et al. (2007); Wilson (2010b) and hardboard by e.g. González-García et al. (2009b, 2011). However, the majority of these studies only assessed the cradle-to-gate impacts of wood-based products and aspects like carbon storage and delayed emission dynamics were not addressed. Moreover, only a few studies (e.g. Dias et al. 2012) compared different methodologies to estimate CFs, and a comprehensive assessment of the influence of different methodological issues in the results is still lacking, namely regarding wood-based panels.

The purpose of this article is twofold. Firstly, it aims at assessing the CF of particleboard produced in Portugal. Secondly, it aims at assessing the influence of different methodological issues in the particleboard CF calculation by comparing four different CF methodologies: i) ISO/TS 14067; ii) the GHG Protocol Product Standard; iii) PAS 2050; iv) the Climate Declaration. In Portugal, there is an important production of particleboard (more than 50% of the wood-based panel production) and the wood industry as a whole represents about 14% of the industrial gross national product and 11% of exports (AIMMP, 2010).

This article is structured in five sections including this introduction. Section 2 briefly presents the four CF methodologies. Section 3 describes the life-cycle model developed as well as the main methodological differences between the four methodologies. Section 4 presents and discusses the results, focusing on the contribution of different methodological issues. Finally, Section 5 draws the conclusions together.

2. Carbon footprint methodologies

This section introduces the four CF methodologies used to assess the CF of particleboard: i) ISO/TS 14067; ii) the GHG Protocol Product Standard; iii) PAS 2050; iv) the Climate Declaration. The first three are specific standards or specifications to calculate the CF of products, while the Climate Declaration is a subset of an Environmental Product Declaration, which assesses several environmental impacts.

The recently published Technical Specification ISO/TS 14067 (ISO/TS, 2013) provides specific requirements and guidelines for the quantification and communication of the CF of products, based on existing ISO standards on life cycle assessment (ISO, 2006a, 2006b) and on environmental labels and declarations (ISO, 2000, 2006c). In particular, it provides requirements for the treatment of specific GHG emissions and removals (e.g. fossil and biogenic carbon, carbon storage in products, land-use change) and additional requirements for the communication of the CF.

The GHG Protocol Product Standard, from the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), was published in 2011 and provides requirements to quantify the GHG inventories of products and also requirements for public reporting (WRI and WBCSD, 2011). It is based on a LC and attributional approach and builds on the ISO standards for LCA (ISO, 2006a, 2006b) and the first version of PAS 2050 (BSI, 2008). In order to enable meaningful comparisons between products, the development and use of sector specific rules, termed ‘product rules’, is promoted. Nevertheless, no product rules for particleboard were available and the general GHG Protocol Product Standard was applied.

The Publicly Available Specifications (PAS) 2050, from the British Standard Institution, also builds on the existing ISO 14040 and 14044 standards for LCA (ISO, 2006a, 2006b) and further specifies them for the assessment of the LC GHG emissions of goods and services (BSI, 2011). It was first introduced in 2008 (BSI, 2008) and was revised in 2011 (BSI, 2011), in alignment with the GHG Protocol Product Standard (WRI and WBCSD, 2011) regarding key topics (e.g. sector/product rules, biogenic carbon, recycling, land-use change, delayed emissions) (for details, please refer to BSI et al., 2011). PAS 2050 sets directions on how to deal with several common methodological issues such as system boundary definition and allocation as well as more specific issues, for example carbon storage and delayed emissions. The latter are particularly important in the context of wood-based panels and are discussed in Section 3.3. However, PAS 2050 does not give specific guidelines for products or sectors. Instead, similarly to the GHG Protocol, it recommends the use and development of sector specific rules known as 'supplementary requirements'. General PAS 2050 guidelines were applied to the particleboard case study, since no supplementary requirements were available.

A Climate Declaration is a single-issue environmental product declaration (EPD) focused on GHG emissions. This concept was first introduced by the International EPD system (IEC, 2008a). The Climate Declaration builds on the same standards as a full EPD, namely ISO 14040 and 14044 standards for LCA methodology and ISO 14025 standards for environmental declarations (ISO, 2006a, 2006b, 2006c). The assessment is based on specific guidelines, termed Product Category Rules (PCR), developed for each product category (i.e. group of products that can fulfill equivalent functions). In particular, PCRs define a similar set of rules for calculating the environmental or climate impacts of products within the same product category, e.g. functional unit, system boundary, allocation rules, cut-off criteria. There are various EPD program operators which results in duplicate PCRs and lack of harmonization between them (Ingwersen and Stevenson, 2012; Subramanian et al., 2012). The PCR for particleboard used to assess the Climate Declaration in this article is the most recent one developed in the context of the International EPD System, a well-known and internationally recognized EPD program (Environdec, 2012).

3. Methods

3.1 System boundary and functional unit

A LC model was developed for particleboard produced in Portugal, which served as the basis for the application of the different CF methodologies. Fig. 1 shows the LC model flowchart. A particleboard is a wood-based panel made from wood particles, mainly wood residues from different sources, usually aggregated using urea-formaldehyde (UF) resin. The wood used to produce particleboard is assumed to come from four different sources: sawmill co-products (30%), post-consumer waste wood (30%), pine (*pinus pinaster*) forest residues (25%) and eucalypt (*eucalyptus globulus*) forest residues (15%), which represents the typical particleboard produced in Portugal (Garrido et al., 2010). A functional unit of 1 m^3 of uncoated particleboard for non-structural use (density of 640 kg/m^3) was defined based on the PCR for the Climate Declaration, which is the only methodology assessed that establishes a specific functional unit for this product.

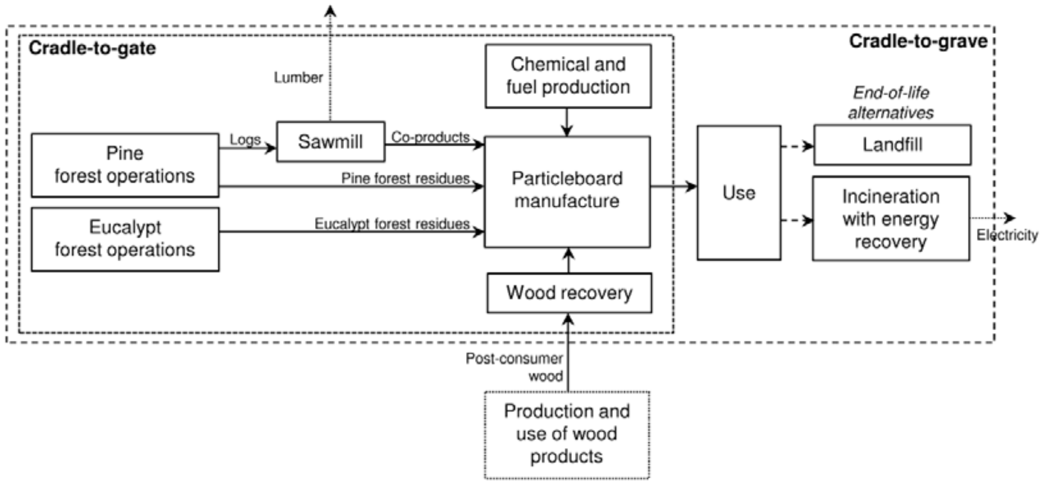

Fig. 1 System boundary of the particleboard life-cycle model.

Both cradle-to-gate and cradle-to-grave models were developed to enable a more comprehensive assessment. This is also consistent with the Climate Declaration, which clearly defines downstream processes as optional and states that these must be defined separately. The cradle-to-gate model includes the pine forest operations (site preparation, planting and logging, including harvesting and forwarding), the eucalypt forest operations (logging), the sawmill process, the post-consumer waste wood recovery process and the particleboard production. In addition, it takes into account the production of fuels, electricity, urea-formaldehyde (UF) resin and other chemicals as well as transport of raw and ancillary materials. No land-use change was considered since pine forest area in Portugal has been decreasing since 1970 (ICNF, 2013). The cradle-to-grave model also includes transport of particleboards to the distribution platform and two alternative end-of-life (EoL) scenarios: incineration with energy recovery and landfill disposal. The main simplifications and exclusions to these models due to the application of the various CF methodologies are described in the next section.

3.1.1 Cut-off criteria, capital goods and other exclusions

Cut-off criteria are established to determine the input and output flows to be included in the assessment. ISO/TS 14067 states that if cut-off criteria are used their effect on the outcome of the study shall be assessed and refers to ISO 14044 for additional guidance (ISO, 2006b, 4.2.3.3.3). The GHG Protocol allows exclusions based on significance when a data gap exists (the definition of insignificance is established by the company). PAS 2050 and the Climate Declaration require the inclusion of all the processes that contribute to more than 1% of the anticipated LC GHG emissions of the functional unit and at least 95% of the total GHG emissions associated with the product. These cut-off criteria combined with the different allocation approaches (see Section 3.4) result in the exclusion of different unit processes by the four methodologies, as presented in Table 1. The cut-off in PAS 2050 was 98% and in the Climate Declaration 99%.

Table 1 Unit processes excluded from the particleboard system boundary due to cut-off criteria.

	Unit processes excluded due to cut-off criteria[a]	
	PAS 2050	Climate Declaration
Biomass[b]	Pine residue harvesting; Eucalypt residues harvesting; Chip and shaving production	Pine residue harvesting; Eucalypt residue harvesting
Chemicals	Ammonium sulfate production	Ammonium sulfate production

[a] No cut-off criteria was applied in ISO/TS 14067 and the GHG Protocol.
[b] GHG removals were included (only GHG emissions were excluded).

According to PAS 2050 and the PCR for the Climate Declaration, the production of capital goods (e.g. building of site, infrastructure and equipment, their maintenance and decommissioning), transport of workers to and from the place of work and transport of costumers to and from the point of purchase shall be excluded from the system boundary. The GHG Protocol does not require "non-attributable" processes (i.e. not directly connected to the studied product, such as capital goods) to be included, but encourages their inclusion when relevant (WRI and WBCSD, 2011, pp. 42). On the other hand, ISO/TS 14067 only allows exclusions if they do not significantly affect the overall conclusions. Capital goods, namely infrastructure processes, were excluded from the system boundary in the GHG Protocol, PAS 2050 and Climate Declaration assessments.

3.2 Data collection

Unit process data for the assessment of the particleboard CF is the same for all the methodologies. Primary data for Portugal was collected in the context of research projects and thesis at the Center for Industrial Ecology, University of Coimbra. Some of this data is available in Nunes (2008); Nunes and Freire (2007); Garcia (2010); Garcia and Freire (2011); Freire and Marques (2012). Fuel consumption (diesel and gasoline) in eucalypt and pine forest activities were estimated based on Nunes (2008) and Dias et al. (2007), respectively. Electricity generation for the main processes was modeled with reference to the 2010 Portuguese mix (Freire and Marques, 2012). Average transport distances for Portugal were assumed for materials used in the main production processes and distribution of particleboards. Transport of inputs was done by truck with a payload of 20-27 t.

The main sources of secondary data were peer-reviewed literature and databases (mainly Ecoinvent v.2, Ecoinvent, 2012). Data regarding the sawmill process was collected from Milota et al. (2006) and the production of UF resin was modeled based on Wilson (2010c). The main data source for the particleboard manufacturing process was Rivela et al. (2006). Recovering of post-consumer waste wood was modeled based on Merrild and Christensen (2009).

Regarding particleboard end-of-life, GHG emissions from incineration were assumed similar to those from wood. Ecoinvent data for incineration with energy recovery of wood was considered (Doka, 2009). GHG emissions from the decomposition of particleboard in landfill were calculated according to Wang et al. (2011), which estimates the degradability of particleboard in landfill to be 1.3%. Emissions were assumed to be released at a constant rate during the first 20 years after landfill disposal, according to Micales and Skog (1997) (0.8% of carbon is released as methane and 0.5% as carbon dioxide).

3.3 Biogenic carbon: carbon storage and delayed emissions

During biomass growth, there is an uptake of carbon (C) from the atmosphere through photosynthesis (C uptake) which is temporarily stored in wood-based products (biogenic C storage). This stored C may be re-emitted to the atmosphere during the LC of the product (delayed emission of temporarily stored C) or be indefinitely stored as a result of waste management (e.g. in landfill). When stored C is left out of the atmosphere for a certain period of time, its effect on global warming is postponed (Brandão and Levasseur, 2011; Brandão et al., 2013). Fig. 2 illustrates the concepts of biogenic carbon storage and delayed emission of temporarily stored carbon for two particleboard EoL scenarios.

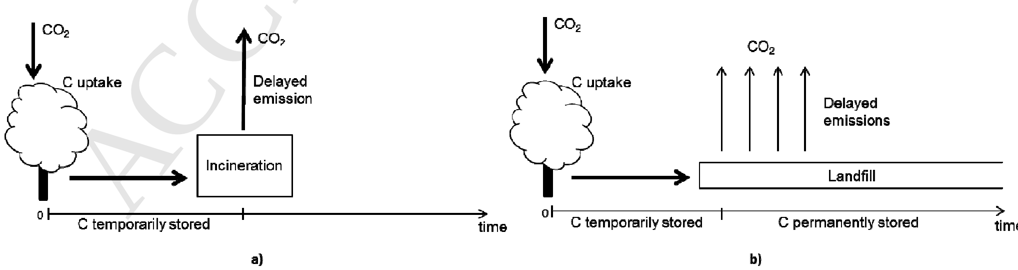

Fig. 2 Schematic diagram of carbon storage and delayed emissions of the temporary stored carbon for two particleboard end-of-life scenarios: a) incineration; b) landfill disposal.

The current approach to treat biogenic CO_2 emissions (emissions of C temporarily stored in biomass) in LCA and CF studies is often to exclude them from the assessment, as it is assumed that the same amount of CO_2 was previously sequestered by biomass, giving a net zero emission (Guinée et al., 2002; Hischier et al., 2010). However, it is increasingly acknowledged that biogenic CO_2 should be taken into account, since not considering it could lead to accounting errors (Searchinger et al, 2009; Bird et al., 2010). On the other hand, even when C uptake during biomass growth is accounted for (as a negative emission) as well as the subsequent release (as a positive emission), the duration of storage is usually disregarded, i.e. the effect of delaying the emission of the temporarily stored C is not taken into account (Brandão et al., 2012). The different CF methodologies adopt different approaches to these issues.

The PCR for the Climate Declaration excludes both the uptake and the emission of biogenic CO_2 from the global warming calculations, and C storage in wood products is not taken into account. On the other hand, ISO/TS 14067, the GHG Protocol and PAS 2050 explicitly include in the CF assessment both emissions to and removals from the atmosphere from biogenic sources. Regarding C storage, the GHG Protocol requires that the amount of C contained in the product in cradle-to-gate inventories is reported and that C not released to the atmosphere during waste treatment, therefore considered permanently stored, is also reported. In PAS 2050, the portion of removed C not emitted to the atmosphere during the 100-year assessment period is treated as stored C and accounted for in the CF calculation. On the other hand, in ISO/TS 14067, C storage in products shall be reported separately in the CF study report and not included in the CF.

Due to the relatively long service life and/or end-of life time period of particleboard, the effect of delayed emissions may be important to the particleboard CF calculation. The use of a weighting factor to calculate the effect of delayed emissions is optional in ISO/TS 14067, the GHG Protocol and PAS 2050. If the effect of delayed emissions is taken into account, it shall be documented separately. In ISO/TS 14067 and the GHG Protocol no recommended method is provided for delayed emission assessment. Therefore, a sensitivity analysis was performed using six approaches to understand the effect in the particleboard CF of delayed emissions calculated by different methods: i) the fixed GWP approach; ii) the Lashof approach iii) the Moura-Costa approach; iv) the ILCD handbook method; v) the dynamic LCA approach and vi) the time-adjusted warming potential (TAWP) method. The fixed GWP approach does not take into account the temporal distribution of emissions. It considers that the amount of C stored in biomass is added to the amount of C released at the product end-of-life, i.e. the CO_2 absorbed in photosynthesis is assigned a

GWP of -1, while the biogenic CO_2 released at the end-of-life is assigned a GWP of 1 (Guinée et al., 2009). All the other approaches account for the temporal distribution of emissions. The Moura-Costa (Moura-Costa and Wilson, 2000) and Lashof (Fearnside et al., 2000) methods are explained in further detail in Brandão and Levasseur (2011). Details on the ILCD handbook method can be found in EC JRC (2010). The dynamic LCA method and its application are explained in detail in Levasseur et al. (2010, 2012). The TAWP method is detailed in Kendall (2012).

In PAS 2050, two methods for the calculation of the weighted average impact of delayed emissions based on the Lashof approach (see Clift and Brandão, 2008) are suggested. For emissions delayed up to 25 years from the formation of the product, the delayed single release method shall be used; for longer delay periods, the delayed release method, similar to the ILCD handbook method, shall be used. The two methods used in PAS 2050 apply to all delayed GHG emissions, as CO_2 eq, although care should be taken when a significant amount of non-CO_2 emissions are involved, as these methods were developed specifically for CO_2 emissions and, therefore, the result would be less accurate, as detailed in BSI (2011, Annex E).

The particleboard is composed of about 90% of wood (576 kg/m^3) with an average C content of 52% (Wilson, 2010a), resulting in about 300 kg of stored C per m^3 of particleboard. The particleboard service life is assumed to be 10 years. The chosen time-horizon for the assessment of the particleboard CF is 100 years, which is consistent with all the CF methodologies analyzed and is the most common time horizon used in LCA and CF (Levasseur et al., 2010; WRI and WBCSD, 2011; Brandão et al., 2013). Nevertheless, a sensitivity analysis to the time-horizon was also performed, presented in Section 4.2. Fig. 3 shows the biogenic C content of the particleboard over 100 years following the formation of the product for the two end-of-life scenarios: incineration (the biogenic C is released after the 10-year service life, i.e. it is temporarily stored for 10 years) and landfill disposal (1.3% of the biogenic C is released after the 10-year service life at a constant rate during the following 20 years, i.e. 98.7% of the C is permanently stored and 1.3% is temporarily stored for 20 years on average). C is assumed to be taken up at year 0 of formation of the product, i.e. the timing of C uptake in forest is not considered, which complies with ISO/TS 14067 and PAS 2050. Although recent studies addressing this issue (e.g. Cherubini et al., 2011; Levasseur et al., 2012) showed that results are sensitive to the temporal boundary, this is out of the scope of this article.

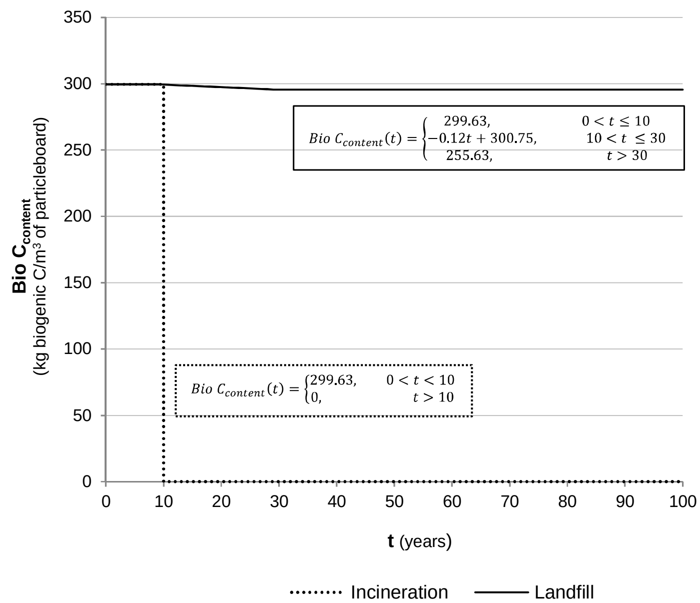

Fig. 3 Biogenic carbon content of particleboard over 100 years after the formation of the product.

Table 2 shows the factors calculated with different methods to account for the delayed emission of 1 kg of CO_2 at particleboard EoL. These factors reflect the time of delay in the emissions for each EoL scenario, according to the biogenic carbon content profile presented in Fig. 3 (except for the fixed GWP approach, which does not account for the timing of emissions). For the incineration scenario, the values were obtained for a delay of 10 years in the emission of 1 kg of biogenic CO_2 and represent the impact of that delayed emission. For the landfill scenario, the values were calculated considering that 1 kg of biogenic CO_2 is emitted at a constant rate during 20 years (0.05 kg CO_2/year) between the 10th and 30th year following formation of the product and represent the total impact of those delayed emissions. By multiplying these factors by the total biogenic CO_2 emissions arising at the particleboard EoL, the impact of these emissions reflecting the timing of release according to the different methods is obtained (this can be guaranteed for the landfill scenario since the emission release is assumed linear). In PAS 2050, the same factors, termed weighting factors, apply to the other GHG emissions (as CO_2 eq) arising at the EoL of particleboard. In dynamic LCA and the TAWP model, different characterization factors were calculated for the other type of GHG emission (namely CH_4), according to Levasseur et al. (2010) and Kendall (2012), respectively.

Table 2 Factors reflecting the delayed impact of particleboard end-of-life (EoL) biogenic CO_2 emissions.

Methods to assess delayed emissions	Delayed impact of 1 kg of biogenic CO_2 emitted at particleboard EoL	
	Incineration	Landfill[a]
Fixed GWP	1	1
Lashof	0.924	0.850
Moura-Costa	0.791	0.592
ILCD	0.900	0.805
Dynamic LCA	0.924	0.848
$TAWP_{100}$	0.922	0.845
PAS 2050	0.924[b]	0.805[c]

[a] Considers that 1 kg of biogenic CO_2 is emitted at a constant rate during 20 years (0.05 kg CO_2/year) between the 10th and 30th year following formation of the product (see Fig. 3).
[b] Delayed single release method (see BSI, 2011, Annex E for more details).
[c] Delayed release method (see BSI, 2011, Annex E for more details).

3.4 Multifunctionality and allocation

Biomass-based production chains are often multifunctional, i.e. they are associated with more than one co-product (Jungmeier et al., 2002a; Malça and Freire, 2006, 2011). In the particleboard LC, there are two multiple output processes: the sawmill process and the end-of-life incineration with energy recovery of particleboard. The treatment of the multifunctionality in those processes by the different methodologies is explained in the next sections.

Forest residues, namely logging residues, resulting from forest production for the wood industry or from energy crops were considered as residues with no economic value (waste) and thus (following the standard approach in LCA for waste, e.g Clift et al., 2000; Jungmeier et al., 2002b) no environmental burden resulting from previous processes was allocated to them. Therefore, only collection, transport and further processing of forest residues were included in the calculations performed with the CF four methodologies.

3.4.1 Sawmill

The sawmill process is a multiple output process since it simultaneously produces planned lumber for the construction industry, which is the main product, and sawdust, chips and shavings, co-products with low economic value, which are used in the production of particleboard. Fig 4 shows the flowchart of the sawmill process.

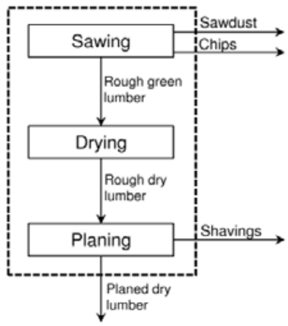

Fig 4 Flowchart of the sawmill process.

The ISO/TS 14067 standards establish a hierarchy of procedures to deal with multifunctional processes based on ISO 14044 (ISO, 2006b), and similar guidance is provided in the GHG Protocol (WRI and WBCSD, 2011). Following these standards, system expansion should be the first option to solve the multifunctionality problem, since subdividing the unit process is not possible due to joint production. However, the application of system expansion to this multi-output system is very complex and was not considered to avoid increasing the complexity of the CF methodology comparison. According to ISO 14044 (ISO, 2006b), whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted. In this article, two allocation methods were used: mass allocation (ma) and economic allocation (ea), since they are used in the CF methodologies addressed. Other allocation methods, e.g. based on the carbon content or energy content of the co-products, were not analyzed observing that the allocation factors for mass, carbon and energy content are similar, which would lead to similar results.

The allocation factors calculated for each method are presented in Table 3. Economic allocation factors were calculated taking into account average annual market prices for 2009 (INE, 2010). Mass balance regarding carbon content of wood was preserved. A sensitive analysis to the influence of the allocation approach was also performed, considering that 100% of biomass inputs to particleboard production come from sawmill co-products (extreme situation), presented in Section 4.2.

Table 3 Allocation factors for sawmill co-products.

Sawmill sub-process	Co-products	Mass allocation	Economic allocation[a]
Sawing	Rough green lumber	56.0%	85.7%
	Sawdust	*7.0%*	*2.3%*
	Chips	*37.0%*	*12.0%*
Planing	Planed dry lumber	85.0%	96.4%
	Shavings	*15.0%*	*3.6%*

[a] INE, 2010.

PAS 2050 uses a similar approach to ISO/TS 14067 and the GHG Protocol. If avoiding allocation is not practicable, supplementary requirements should be used. If none of these procedures is applicable, allocation shall be made according to the economic value of the co-products. In this article, economic allocation was used for the PAS 2050 CF calculations. The PCR for the Climate Declaration defines mass allocation as the approach to deal with multifunctionality and that was used in this study for allocating burdens in the sawmill process.

3.4.2 Incineration with energy recovery

Waste incineration plants may also generate electricity. In Portugal, electricity generated in incineration plants is sold to the grid. Following ISO/TS 14067 and the GHG Protocol approaches, system expansion should be the first option to solve the multifunctionality associated with this joint process. Therefore, the avoided burdens approach was followed for ISO/TS 14067 and the GHG Protocol CF calculation to assess electricity generated in incineration assuming it displaces the Portuguese grid mix. As stated in section 3.2, it was assumed that emissions from particleboard incineration are similar to wood waste incineration. According to Doka (2009), the incineration of 1 kg of waste wood generates about 1.3 MJ of electricity. As a result, the incineration of 1 m^3 of particleboard avoids the generation of about 231 kWh of electricity from the grid, i.e. avoids the emission of about 90 kg CO_2 eq/m^3 of particleboard, as the GHG intensity of the Portuguese electricity grid was estimated as 390 g CO_2 eq/kWh in 2010 (Freire and Marques, 2012).

The PAS 2050 has a specific procedure to deal with multifunctionality in waste combustion with energy recovery: both GHG emissions and removals shall be allocated to energy generation. Therefore, only transport of waste to the incineration plant was considered within the particleboard system boundary. The Climate Declaration addresses this issue in the opposite way since it applies the “polluter-pays” approach. It considers that “the environmental impacts of collecting and transportation of the waste to the incineration plant as well as those impacts caused by the incineration process itself are allocated to the waste generator" (IEC, 2008b, pp. 14). Following this approach, all the burdens from the incineration process were allocated to the particleboard LC in the Climate Declaration CF calculation.

4. Results and discussion

This section presents and discusses the CF calculated by the four methodologies (ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration). Firstly, the cradle-to-gate CF is assessed and the main hotspots in the production of particleboard are identified. Secondly, a cradle-to-grave assessment is presented considering two end-of-life (EoL) scenarios: incineration with energy recovery and landfill disposal. The contribution of different methodological issues to the differences in results is discussed, particularly the inclusion or exclusion of capital goods, the approaches used to deal with multifunctional processes, the cut-off rules and the influence of using different methods to assess delayed GHG emissions.

4.1 Cradle-to-gate assessment

Fig. 5 compares the cradle-to-gate CF of particleboard calculated by the four CF methodologies and shows the relative contribution of each LC stage. There is a major difference in the reported CF between the methodologies that include (GHG Protocol, PAS 2050) and exclude (ISO/TS 14067, Climate Declaration) biogenic carbon storage. The GHG Protocol (mass allocation, ma) and PAS 2050 calculated negative CFs (-913 and -939 kg CO_2 eq/m^3, respectively) while ISO/TS 14067 (ma) and the Climate Declaration calculated positive CFs (188 and 168 kg CO_2 eq/m^3). It should be noted that carbon stored in particleboard (equivalent to 1098 kg CO_2/m^3) shall be reported separately in ISO/TS 14067 CF report and is shown in a separate column in Fig. 5. The GHG Protocol also requires that the amount of carbon embedded in the product is reported when performing a cradle-to-gate assessment (highlighted in Fig. 5). Reporting the amount of C stored in the product is particularly important in cradle-to-gate assessments in order to avoid misleading comparisons with other products, since the embodied carbon at gate may be released later during use or end-of-life phase (i.e. may be only temporarily stored).

For the ISO/TS 14067, GHG Protocol and PAS 2050 CF, the biomass production stage had a high contribution to GHG removals, due to the uptake of CO_2 from the atmosphere during tree growth. On the other hand, the industrial process was the one contributing the most to GHG emissions due to the biogenic CO_2 released in the combustion of biomass for energy purposes. For the Climate Declaration, the relative contribution of LC stages to the CF differs from the other methodologies, since emissions and removals of biogenic CO_2 are not included. For the CF calculated using the Climate Declaration, the UF resin production had the largest contribution (40% of GHG emissions). The industrial process stage contributed 36% to the total. The main source of GHG emissions in the UF resin production were the production of urea (67%), due to ammonia production (47%). In the industrial process, the major contributor to the GHG emissions was the combustion of natural gas for wood drying. The other LC stages individually contributed to less than 10% of the total CF.

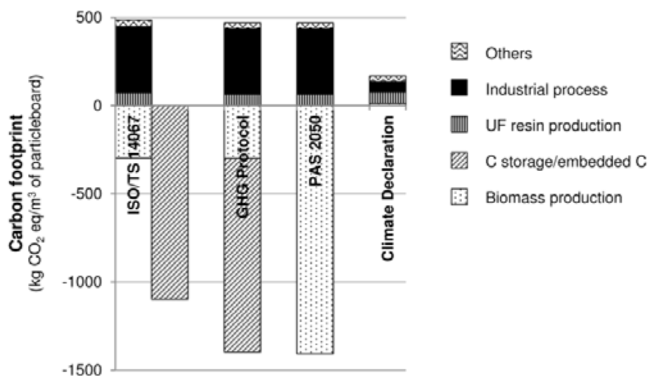

Fig. 5 Carbon footprint of particleboard (cradle-to-gate assessment). Results for ISO/TS 14067 and GHG Protocol are for mass allocation in the sawmill process. Others include energy inputs, transport of inputs and production of other chemicals.

4.2 Cradle-to-grave assessment

Table 4 shows the cradle-to-grave CF of particleboard obtained for the different CF methodologies for the two end-of-life (EoL) scenarios and allocation approaches to sawmill co-production (mass, ma and economic, ea). A great variation in results can be observed among the various CF methodologies for both EoL scenarios. Moreover, the ranking of EoL scenarios strongly depends on the CF methodology used. For the methodologies that include biogenic carbon storage (GHG Protocol, PAS 2050), the scenario with landfill disposal had always a lower carbon footprint than the incineration one. This result diverges from the EU Landfill Directive which sets narrow targets for diverting biodegradable waste from landfill and gives preference to other waste management practices such as recycling or incineration (European Commission, 1999). However, landfilling may be preferable from a GHG standpoint in this case but may not be environmentally better, since a GHG-only assessment cannot be considered a full environmental assessment.

Table 4 Carbon footprint of particleboard (cradle-to-grave assessment).

CF methodologies	CF (kg CO_2 eq/m^3 of particleboard)			
	Incineration		Landfill	
	ma	ea	ma	ea
ISO/TS 14067[a]	140	133	433 *(-1092)*	426 *(-1092)*
GHG Protocol	113	107	-682	-688
PAS 2050		189		-692
Climate Declaration	201		287	

ma: mass allocation (sawmill); ea: economic allocation (sawmill).
[a] Carbon storage reported as a negative value within parentheses.

Regarding landfill scenarios, where only part of the C stored in particleboard is released, contradictory results were obtained depending on the inclusion or exclusion of biogenic carbon storage. A positive CF was calculated using the Climate Declaration and ISO/TS 14067, although the latter also provides information about C stored (reported as a negative value within parentheses in Table 4). On the other hand, both PAS 2050 and the GHG Protocol calculated negative CF, meaning that particleboard landfilling may act as a carbon sink. Carbon stored in landfill is estimated to be equivalent to 1092 kg CO_2/m^3 of particleboard.

Differences in results in the incineration scenario were less significant but reached 47% (Climate Declaration vs. GHG Protocol ea). The differences observed were due to different approaches to methodological issues, namely the approach used to deal with multifunctionality in the incineration process, the allocation approach in the sawmill process, the inclusion or exclusion of capital goods, and the cut-off criteria. The major difference in the results was due to the approach used to deal with multifunctionality in the incineration process. By crediting the avoided burden from grid electricity generation, the ISO/TS 14067 and GHG Protocol CFs were reduced by 39-46%. If no electricity credit was assigned to particleboard, the CF calculated with ISO/TS 14067 and the GHG Protocol would be 10 to 18% higher than that calculated with the Climate Declaration and PAS 2050. The ISO/TS 14067 and GHG Protocol CFs are thus highly dependent on the GHG intensity of the electricity grid.

The differences between ISO/TS 14067 and the GHG Protocol CFs reached 20% and were due to the exclusion of capital goods in the latter. If capital goods were taken into account in the Climate Declaration and PAS 2050 CF, they would represent about 12% of the particleboard CF. Crediting avoided burdens in ISO/TS 14067 and the GHG Protocol CFs enlarged the relative share from capital goods. The contribution of capital goods in the particleboard CF is in line with the findings of other authors that addressed the environmental relevance of capital goods in LCA of wooden construction materials (Frischknecht et al., 2007). This contribution was calculated relatively to the CF of particleboard (incineration scenario) in which most of the GHG emissions are biogenic CO_2 (neutral due to the uptake of CO_2). Thus, there is a higher relative contribution of capital goods comparatively to fossil-energy-based industrial processes. Despite the exclusion of capital goods being a common practice in LCA studies (Frischknecht et al., 2007), results show that they have a significant impact for particleboard and should not be neglected. Although not mandatory, the GHG Protocol encourages the inclusion of capital goods if relevant and the PAS 2050 refers to supplementary requirements for guidance on this issue. Therefore, the development of supplementary requirements or product rules for particleboard could have an important role here.

The cut-off criteria, on the other hand, had a negligible contribution to the differences in results. Regarding the allocation approach in the sawmill process, small differences in results can be observed between mass and economic allocation results (about 5%) since sawmill co-products represent less than 30% of the mass input to particleboard production and biomass production has a small contribution to the overall GHG emissions of particleboard. Nevertheless, as wood raw material is becoming scarce, there is a tendency to use more recovered wood in particleboard production, e.g. sawmill co-products (Irle and Barbu, 2010). The importance of the allocation approach increases as the share of sawmill co-products in particleboard increases. A sensitive analysis to the influence of the allocation approach was performed, considering that 100% of biomass inputs to particleboard production come from sawmill co-products (extreme situation). Fig. 6 shows the particleboard CF calculated for both the reference system and the 100% sawmill co-product situation. As can be seen, differences in results between the CF methodologies were higher for the latter, reaching 51% for the Climate Declaration versus the GHG Protocol (ea) (against 47% in the reference system). The allocation approach can account up to a 9% difference in CF results (ISO/TS 14067 ma vs. ea) when 100% of biomass comes from sawmill co-products. This difference is, however, much lower than for other biomass systems (Werner et al., 2007; Malça and Freire, 2006, 2011) since allocation of emissions occurs very early in the particleboard supply chain and the overall GHG emissions associated with the sawmill (and upstream) process are low (about 17% of the overall particleboard CF).

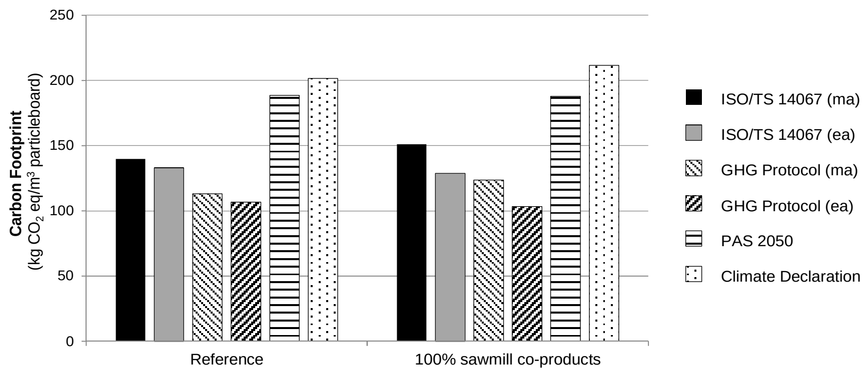

Fig. 6 Comparison of the CF of the reference particleboard and of the particleboard with 100% sawmill co-products, for the incineration EoL scenario.

4.2.1 Delayed emissions

Although not mandatory in any of the CF methodologies analyzed, accounting for the effect of timing of emissions may be performed. Only PAS 2050 prescribes a specific method for assessing delayed emissions. For both ISO/TS 14067 and the GHG Protocol, six alternative methods were assessed. It should be noted that, in ISO/TS 14067, if emissions occur within ten years after the production of the product, as in the incineration scenario, they shall be assessed as occurring at the beginning of the assessment period. As a result, the effect of timing of emissions was not assessed in ISO/TS 14067 for the incineration scenario and, for that reason, the GHG Protocol results were chosen to be presented. Table 5 shows the GHG Protocol CF of particleboard for the two EoL scenarios calculated taking into account the effect of timing of emissions according to the six methods and the PAS 2050 CF calculated using its specific method. The effect of timing of emissions was also taken into account when calculating the avoided burden credit in the incineration scenario.

The method used to assess delayed emissions had a significant influence in the particleboard CF results for the incineration scenario, where all the stored C is released. Using the Moura-Costa and the ILCD approaches to account for delayed emissions of the stored C lead to a negative CF, since the credit for these emissions is higher than the cradle-to-gate GHG emissions including the avoided burdens credit. However, the reduction was lower with the Moura-Costa approach, since a yearly delayed GHG emission in ILCD is considered to have a higher relative impact. The Lashof, dynamic LCA and TAWP approaches gave similar results and the CF was reduced by 81-82% compared to the fixed GWP approach. In absolute terms, similar time adjusted emissions were calculated for the Lashof, dynamic

LCA and TAWP100 approaches (less than 0.2% difference), as emissions occur within 25 years and non-CO_2 emissions are irrelevant, which is consistent with Kendall's (2012) conclusion. In the PAS 2050 assessment taking into account the impact of delayed emissions, the decrease in the particleboard CF compared to the single release assessment (see Table 4) is insignificant, since only emissions from transport of waste to the incineration plant were accounted for as delayed emissions and these represent less than 5% of total emissions. In the landfill scenario, the use of different methods to account for delayed emissions lead to less significant differences in results (less than 12%), since most of the biogenic carbon is permanently stored.

Table 5 Sensitivity analysis to the method used to assess delayed emissions (results for the GHG Protocol, mass allocation).

Method used to assess delayed emissions	CF (kg CO_2 eq/m^3 particleboard)	
	Incineration	Landfill
Fixed GWP	113	-688
Lashof	22	-715
Moura-Costa	-138	-771
ILCD	-7	-732
Dynamic LCA	21	-720
$TAWP_{100}$	20	-680
PAS 2050[a]	188[b]	-745

[a] CF calculated based on PAS 2050 CF presented in Table 4 (not the GHG Protocol).
[b] Only accounts for delayed emissions from transport of waste to the incineration plant.

The results presented in Table 5 are for a 100 year-time horizon. A sensitivity analysis to assess the implications of using different time horizons (20- and 500-year) was also performed, as recommended by Brandão et al. (2013). Table 6 shows the CF calculated with the GHG Protocol methodology using the fixed GWP approach, the dynamic LCA method and the TAWP method for three different time horizons. No values were calculated using PAS 2050 and the ILCD delayed emission methods, since these methods are applied to 100-year time-horizon only.

The major differences in results for the three time horizons in the incineration scenario occur for the dynamic LCA and TAWP methods, which account for the timing of emissions. These two methods presented similar results. A negative CF was calculated for the 20-year time horizon due to the storage period being half of the assessment period, which resulted in a relative impact of 0.55 and 0.53, respectively, for each unit of CO_2 emitted in particleboard incineration. For these methods, the longer the time horizon, the higher the CF, since the time of storage becomes less important. In landfill, the 20-year

CF calculated with these methods is lower than the 100-year, since emissions occurring after 20 years of the formation of the product are not accounted for. The fixed GWP approach does not account for the timing of emissions and does not have any cut-off in the assessment period. As a result, the shorter the time horizon, the more important non-CO_2 GHG emissions are and the higher the CF is. Regarding the landfill scenario, differences can reach 67%, due to CH_4 emissions. On the other hand, no major changes occur in the incineration scenario (about 13%), since most of the GHG emissions in the particleboard LC are CO_2. Despite the differences in the CF, the same conclusions can be drawn regarding the ranking of EoL scenarios.

Table 6 Comparison of the GHG Protocol CF results calculated for three time horizons with different methods (in kg CO_2 eq/m^3 of particleboard).

Method used to assess delayed emissions	Incineration			Landfill		
	20 yrs	100 yrs	500 yrs	20 yrs	100 yrs	500 yrs
Fixed GWP	125	113	109	-286	-688	-860
Dynamic LCA	-327	21	92	-777	-720	-855
TAWP	-357	20	95	-770	-680	-837

5. Conclusions

Different methodologies can be used to quantify the carbon footprint (CF) of wood-based panels. This article compared the CF of particleboard calculated using ISO/TS 14067, the GHG Protocol Product Standard, PAS 2050 and the Climate Declaration. A controversial topic in the CF calculation is biogenic CO_2 accounting and CF methodologies treat this issue differently. As a result, a wide range of CF was calculated: cradle-to-gate from -939 to 188 kg CO_2 eq/m^3; cradle-to-grave from 107 to 201 kg CO_2 eq/m^3 (incineration) and -692 to 433 kg CO_2 eq/m^3 (landfill). ISO/TS 14067, the GHG Protocol and PAS 2050 explicitly include both emissions and removals of biogenic CO_2 in the CF calculation. It should be noted that in ISO/TS 14067 carbon storage is excluded from the reported CF, which leads to higher values (cradle-to-gate and cradle-to-grave landfill scenario) than those reported by the GHG Protocol and PAS 2050; nevertheless, since carbon storage is reported separately, similar conclusions can be drawn. On the other hand, the Climate Declaration does not account for biogenic CO_2 and does not present any information regarding carbon storage.

Not including carbon storage in the assessment of the carbon footprint of wood-based products may bias the comparison with competing products that do not store biogenic carbon (e.g. fossil-based materials). In fact, when a fraction of the biogenic C is permanently stored, as in landfill, the notion of carbon neutrality frequently attributed to biogenic CO_2 emissions is misleading, as discussed in Levasseur et al. (2012). On the other hand, when presenting cradle-to-gate results, the embedded carbon should be reported, in order to avoid misleading comparisons with other products, since the embodied carbon at gate may be released later during use or end-of-life phase (e.g. through incineration). Therefore, in future guidelines for wood-based panels, such as Product Category Rules and Supplementary Requirements, transparent accounting for biogenic CO_2 emissions and removals, including reporting of carbon storage, should be required so that the implications of these issues to the overall CF are comprehensively understood.

The CF of particleboard for the incineration scenario was very sensitive to the treatment of multifunctionality in the incineration process. Although ISO/TS 14067, the GHG Protocol and PAS 2050 have a similar procedure to deal with multifunctional processes in general (based on ISO 14044), PAS 2050 has specific guidelines for allocation of burdens from energy recovery from waste which do not comply with the standard ISO 14044 approach. The Climate Declaration also deals with this issue differently. The treatment of multifunctionality in energy recovery from waste should thus be aligned between CF methodologies.

Other controversial topic in the CF calculation is delayed emissions accounting, which may significantly affect CF results, especially if long-living products are being assessed (80-200% reduction in particleboard CF). The different CF methodologies do not require that the effect of delaying emissions is reported and if delayed emissions are calculated, they are required to be reported separately. The Climate Declaration is the exception, since no reference to delayed emission accounting is made. Despite the consensus in delayed emission reporting between ISO/TS 14067, the GHG Protocol and PAS 2050, no consistent methodology is defined. If companies wish to report the effect of delayed emissions, a sensitivity analysis to the method chosen should be performed since it can lead to very distinct results.

Regarding other methodological issues addressed, attention should be paid to the inclusion of capital goods since these may be important. In fact, CF methodologies, in particular the GHG Protocol, PAS 2050 and the Climate Declaration, tend to ignore capital goods as a general rule. However, in wood-based products the relative contribution of capital goods is higher comparatively to fossil-energy-based industrial processes since biogenic CO_2 emissions resulting from energy requirements are neutral due to C uptake. Product Category Rules and Supplementary Requirements to be developed for wood-based panels should take this into account.

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