buildings

Review

Environmental Product Declarations of Structural Wood: A Review of Impacts and Potential Pitfalls for Practice

Freja Nygaard Rasmussen *, Camilla Ernst Andersen, Alexandra Wittchen, Rasmus Nøddegaard Hansen and Harpa Birgisdóttir

Department of the Built Environment, Copenhagen Campus, Aalborg University, 2450 Copenhagen, Denmark; caa@build.aau.dk (C.E.A.); alwi@build.aau.dk (A.W.); rnh@build.aau.dk (R.N.H.); hbi@build.aau.dk (H.B.)
* Correspondence: fnr@build.aau.dk

Abstract: The use of wood and timber products in the construction of buildings is repeatedly pointed towards as a mean for lowering the environmental footprint. With several countries preparing regulation for life cycle assessment of buildings, practitioners from industry will presumably look to the pool of data on wood products found in environmental product declarations (EPDs). However, the EPDs may vary broadly in terms of reporting and results. This study provides a comprehensive review of 81 third-party verified EN 15804 EPDs of cross laminated timber (CLT), glulam, laminated veneer lumber (LVL) and timber. The 81 EPDs represent 86 different products and 152 different product scenarios. The EPDs mainly represent European production, but also North America and Australia/New Zealand productions are represented. Reported global warming potential (GWP) from the EPDs vary within each of the investigated product categories, due to density of the products and the end-of-life scenarios applied. Median results per kg of product, excluding the biogenic CO_2, are found at 0.26, 0.24, and 0.17 kg CO_2e for CLT, glulam, and timber, respectively. Results further showed that the correlation between GWP and other impact categories is limited. Analysis of the inherent data uncertainty showed to add up to ±41% to reported impacts when assessed with an uncertainty method from the literature. However, in some of the average EPDs, even larger uncertainties of up to 90% for GWP are reported. Life cycle assessment practitioners can use the median values from this study as generic data in their assessments of buildings. To make the EPDs easier to use for practitioners, a more detailed coordination between EPD programs and their product category rules is recommended, as well as digitalization of EPD data.

Keywords: life cycle assessment; structural wood; EN 15804; environmental product declaration; biogenic CO_2; carbon footprint; building design; material choice

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1. Introduction

Activities of the building and construction sector contribute notably to environmental impacts. For instance, as much as 39% of global CO_2 emissions are associated with the construction and use of buildings [1]. Almost one third of these emissions arise from the production of building materials [2]. Additionally, the sector uses vast amounts of energy, mineral, and metal resources for construction as well as operation of existing buildings [3]. As a response to the negative impacts, the building industry and regulation is moving towards measures to reduce emissions as well as energy and material uses.

For decades, building regulation has mainly focused on energy efficiency in the operational phase. However, recent developments acknowledge the growing importance of embodied impacts of the building and construction sector, i.e., emissions and resource uses embedded in production, use, and end-of-life of materials [4–6]. The sector itself is attentive to the sustainability challenge, and in several countries, regulation is being prepared to tackle the negative environmental side effects of the material production and use. Countries, such as Finland, France, Denmark, Sweden, and New Zealand, are in the process of introducing legally binding regulation to assess and benchmark the environmental impact of buildings by use of life cycle assessment (LCA) [7–10]. Furthermore, front-running companies, investors, organizations, and local authorities in various places have driven a bottom-up course of action towards decreasing the negative effects of the built environment, by implementing low-carbon design strategies and circular economy initiatives [7,11–13].

The use of wood and timber products is gaining increased interest from actors around the building and construction value chain [14,15]. Wood and timber products are seen as sustainable materials to use, because of their renewability (if forests are managed sustainably) and their low degree of energy-intensive processing in the manufacturing step [16,17]. Further, the ability to store biogenic carbon, thus postponing the release of biogenic CO_2 to the atmosphere, is considered an important trait of wood and wood-based products [18,19]. In a review of literature on wooden buildings, Andersen et al. [20] found that the median performance of 226 cases is between 3.9 and 4.7 kg CO_2e/m^2/year depending on the building type. In comparison, a review study of 656 building cases of all types of materials by Röck et al. [5] found a median performance between 6.7 and 17.3 kg CO_2e/m^2/year, indicating that wooden buildings, in general, perform better in LCA studies.

Standardized and credible assessment methods and product data are needed to further the uptake of low-emission building practice within the industry [21,22]. However, as pointed out by Pomponi and Moncaster [23] in their literature review of carbon intensities for a range of material categories, there is a notable discrepancy of results within each category. For instance, carbon intensities range by up to a factor 3.6 for wood products. The authors warn how these data variations may result in serious underestimations of actual environmental impacts if the available data is used without care. This pattern of significant differences due to methodological differences, such as scope and allocation, is well documented in other literature, on a product level [24–26] as well as on a building level [27,28].

A more standardized approach to assessing the emission intensities of products is found within the environmental product declaration (EPD) schemes in use. The ISO 14025 about EPDs has been in use since 2006, and based on this standard, several product category rules (PCRs) have been elaborated within the numerous EPD programs operating with this standard [29]. However, research shows that large inconsistencies of approaches exist between these PCRs, basically making the resulting EPDs unfit for comparisons between different EPD programs [30,31].

Compared to the ISO 14025, the EN 15804 standard introduced in 2012 provides a narrower guidance, dealing only with construction products, and establishing rules for scope, allocation, and impact categories to be covered [32]. The standard thus provided the construction industry with a set of core category rules to streamline the assessment and reporting of environmental impacts from the life cycle of specific products [33]. Since the EN 15804 was first published, the number of EPDs has increased steadily. In parallel, data from EPDs are integrated into databases [34] and into building-LCA tools [35]. The EN 15804 EPDs furthermore provide data used to compare functions across material categories, e.g., insulation [36,37]. Anderson and Moncaster [38] reviewed several hundred EPDs of cement, aggregates, and concrete mixes, thereby providing stakeholders of the building and construction industry with a comprehensive overview of potential data to use in different stages of the building design. They further pointed to the need for more detailed rules for consistency in PCRs and for more transparency in the EPD reports. Other studies of EPDs have emphasized the need for interpretation and uncertainty evaluations of EPDs [39,40] to make them applicable in practice.

Based on the current trends in practice and regulation, actors in the processes of building design are expected to include more considerations on the life cycle performance of their activities. In parallel, the product-level data, as unfolded in EPDs, support the use of wood and timber as a measure to reduce the contributions to global warming. When building designers look for product data on their timber constructions, they are met with a diverse collection of EPDs covering different regions, products, and data uncertainty. This paper aims at supporting the broader uptake of EPD-based information for practice-based LCA of buildings. This is done by reviewing the available EN 15804 EPDs of structural wood products to investigate the following research questions:

- What is the availability of data from third-party verified EN 15804 EPDs on structural wood?
- Which environmental impacts do the EPDs report, and what affects the comparability of the EPDs?
- How may the EPDs be used for informing the building design process, and which potential pitfalls should users be aware of?

2. Methods

2.1. Data Collection Process

The compilation of data was limited to third-party verified EPDs that follow the European Standards EN15804:2012 + A1:2013 and EN15804:2012 + A2:2019 for construction works [32,41]. A study by Jane Anderson, 2021, [42] identifies a comprehensive list of international EPD programs that include EPDs, which apply to the two European Standards for EPDs on construction works, respectively. This study uses the list of EPD programs identified by Anderson as a basis for the systematic compilation of EPDs. Searches were conducted in each of the EPD programs using the search words 'wood' and 'timber' as well as equivalent words in French, Spanish, and German, depending on the geographical scope of the EPD program in question. The systematic search of the EPD programs resulted in 72 EPDs. An additional google search was conducted with the search phrase 'EN 15804 wood timber EPD'. This resulted in an additional 9 EPDs.

Besides only focusing on EPDs concerning construction works, this study considers one type of product exclusively: structural wood elements. We chose this limitation because structural elements most often constitute the greater part of the environmental impact from a building, thereby representing the biggest opportunity to reduce environmental impacts from a building. As a final focus of the data collection process, we only included EPDs that were valid at the time of the data collection, that is spring 2021.

2.2. Data Extraction Criteria

Next, after the data collection process, we extracted data from all EPDs according to a defined set of data extraction criteria. The data extraction criteria were generated to create a solid foundation for the data analysis and consists of a list of criteria that could prove to be relevant in the further analysis. Table 1 presents a comprehensive list of all data extraction criteria.

Table 1. Data extraction criteria used for the EPD review.

Data Extraction Criteria	Description
EPD id	The unique id for every EPD.
EPD owner	The owner of the EPD.
Product identification	A short description of the product including wood type (for instance spruce, pine, or fir) and moisture content.
Product category	Structural wood within one of the four categories: sawn timber, glulam, cross laminated timber, and laminated veneer lumber.
Density	Average density for the product as stated in the EPD.
Validation from/to date	Dates from which the EPD is valid from and to.
Geographical representativeness	Geographical scope that the product in the EPD is valid for
Temporal representativeness	Temporal scope that the EPD represents.

Table 1. *Cont.*

Data Extraction Criteria	Description
European Standard	The European Standard that the EPD is based on, either EN15804:2012+A1:2013 or EN15804:2012 + A2:2019 [32,41]
Product Category Rules	Specific product category rules that the EPD is based on.
Functional Unit	Declared unit defined in the EPD, which serves as a basis for the calculations in the EPD.
LCA database	LCA database used for the calculation of the environmental impacts in the EPD.
LCA software	LCA software used for the calculation of the environmental impacts in the EPD.
System boundaries	System boundaries included in the EPD. The system boundaries are defined according to the European Standards, that is life cycle stages concerning the production stage (A1, A2, A3), the construction stage (A4, A5), the use stage (B1, B2, B3, B4, B5, B6, B7), the end-of-life stage (C1, C2, C3, C4), and finally benefits and loads beyond the system boundary (D) [32,41].
End of life scenarios	End-of-life scenario examined in the EPD. In cases where the EPD entails several end-of-life scenarios (for instance, the landfill scenario, incineration scenario, recycling scenario), all end-of-life scenarios are registered.
Environmental impacts	Environmental impacts per functional unit as stated in the EPD.

2.3. Exclusion Criteria

In the data extraction process, we defined a set of exclusion criteria used to scope the study. One important criterion was the sole focus on structural wood elements' EPDs within one of the four categories, as described in Ramage et al., 2017 [17]

- Sawn timber: Timber cut from logs in different sizes, shapes, and different types of wood.
- Glued laminated timber (glulam): Glued laminated timber comprised of multiple layers of timber bonded together with an adhesive to form structural beams.
- Cross Laminated Timber (CLT): Cross laminated timber comprised of multiple layers of wood panel bonded together perpendicular to one another with an adhesive to form a uniform wood panel with structural properties.
- Laminated Veneer Lumber (LVL): Laminated veneer lumber comprised of multiple layers of thin wood bonded together with an adhesive to form structural elements, such as beams.

In addition, to limit the data extraction process, we chose to only include system boundaries related to the production phase, the construction process phase, the end-of-life phase, and the benefits and loads beyond the system boundary. Figure 1 illustrates the system boundaries included in this study with a blue highlight. The system boundary follows the European Standard for EPDs of construction products [32,41]. The newest version of the European Standard for EPDs sets a minimum requirement that the life cycle stages A1–3, C3, C4, and D should be declared in future EPDs [5].

A final exclusion criterion defined in the study is the focus on a selected range of environmental indicators. A study by Dias et al. (2020) suggests that the environmental indicators acidification potential of land and water (AP), eutrophication potential (EP), and global warming potential (GWP) are the most relevant impact categories for softwoods, hardwoods, and glulam [43]. To further investigate the resource uses of construction wood, we also included the resource use categories abiotic depletion potential (ADPe), total use of non-renewable primary energy resources (PENRT), and total use of renewable primary energy resources (PERT). Table 2 presents a comprehensive list of all environmental indicators investigated in the study. Since the updated EN 15804: A2 defines other environmental indicators to be declared in EPDs than EN 15805: A1, we also included indicators from both versions of the standard in the study.

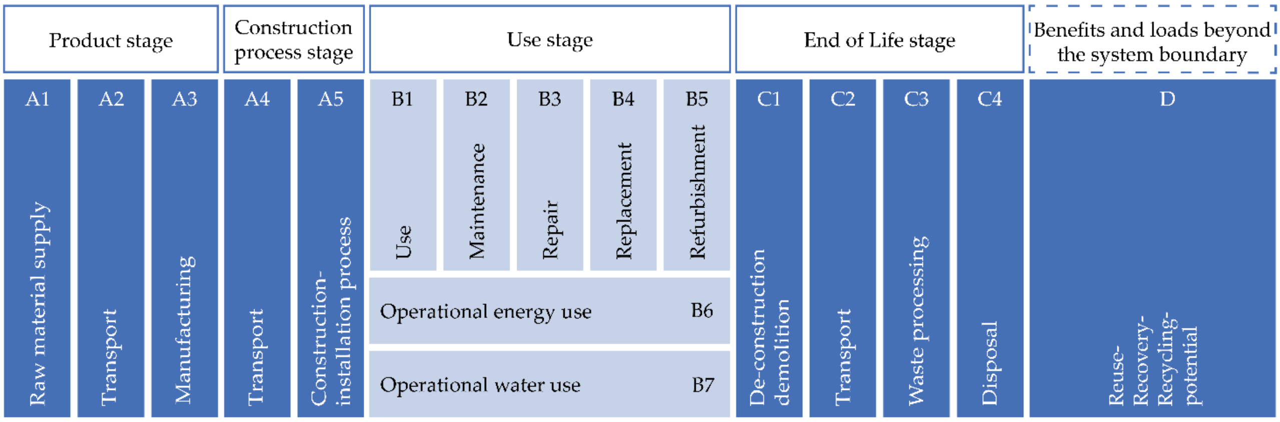

Figure 1. Life cycle stages, as defined in EN 15804, included in the study are highlighted in dark blue.

Table 2. Environmental indicators, units, and which version of the EN 15804 standard they are included in. e denotes equivalents.

Environmental Indicator	Unit	EN 15804
Abiotic depletion potential of fossil resources (ADPE)	kg Sb-e	A1, A2
Acidification potential of land and water (AP)	kg SO_2e	A1, A2
Eutrophication potential (EP)	kg $PO_4{}^3$e	A1
Eutrophication potential (EP)—freshwater	kg $PO_4{}^3$e	A2
Eutrophication potential (EP)—marine	kg N-e	A2
Eutrophication potential (EP)—terrestrial	mol N-e	A2
Global warming potential (GWP)	kg CO_2e	A1, A2
Global warming potential (GWP)—fossil	kg CO_2e	A2
Global warming potential (GWP)—biogenic	kg CO_2e	A2
Global warming potential (GWP)—Land use and land transformation	kg CO_2e	A2
Total use of non-renewable primary energy resources (PENRT)	MJ	A1, A2
Total use of renewable primary energy resources (PERT)	MJ	A1, A2

2.4. Data Normalization

To enable specific levels of comparison between the environmental impact potential results extracted from the EPDs, we normalized all impact potentials to the same unit, namely the unit of environmental indicator per kilogram of product. The normalization was based on the functional unit and the density of the product declared in the EPD and using Equation (1):

$$I_{norm,i} = \frac{I_{i,unit=m^3}}{\rho_i} \tag{1}$$

where $I_{norm,i}$ is the normalized impact potential for the environmental indicator i, I_i is the impact potential for the environmental indicator provided in the unit m^3 in the EPD, and ρ_i is the density of the given product in the unit kg/m^3.

Other comparative analyses in this study require a normalization of results to exclude the biogenic CO_2 embedded in the product. The majority of EPDs declare the amount of biogenic CO_2 in the product. In some other cases, the biogenic carbon is declared, which is then converted into biogenic CO_2 by multiplying with a factor 44/12, which is the factor describing the difference in molar mass between CO_2 and C according to EN 16449. In the few cases where neither biogenic CO_2 nor biogenic carbon were declared, the biogenic CO_2 was calculated based on the calculation rules from standard EN 16449, presented in Equation (2):

$$\frac{44}{12} \times 0.5 \times M_d \tag{2}$$

where 44 and 12 represent the molar mass of CO_2 and C, respectively; 0.5 is the default share of carbon content in wood; and M_d is the dry mass of the wood.

2.5. Uncertainty Assessment

To examine the inherent uncertainty of the EPDs, we performed an uncertainty assessment of all EPDs included in the study. The uncertainty was assessed by applying the method presented in Waldman et al. (2020). Waldman et al. (2020) presents a method that enables a quantitative assessment of the variations in the underlying data in EPDs. The method considers five parameters that can potentially affect the data quality and specificity of EPDs, namely whether the EPDs are:

1. Manufacturer specific.
2. Facility specific.
3. Product specific.
4. Time specific.
5. Supply chain specific.

The first four parameters represent whether the EPD captures an industry or one manufacturer (*manufacturer specific*), multiple facilities or one specific facility (*facility specific*), a range of products or a single product (*product specific*), and a specific point in time or a time period (*time specific*). Finally, the fifth parameter, *supply chain specific*, captures the degree to which the EPD is based on generic upstream data and on upstream data that are representative of the actual processes.

Each of the parameters are given a data quality factor (DQ_f), a Z-value, that quantifies the specificity. If the EPD is specific to the manufacturer, facility, or product, a factor of 2% is applied to the EPD impact potential results for each parameter. If the EPD is not specific to the three parameters, a factor of 20% is applied for each parameter. Parameter 4 about time specificity is set to 20% for all cases, because all EPDs rely on inventory data from past production years. The percentages may be set at different values, but in this study, the percentages for parameters 1–4 follow the defaults described in Waldman et al. [39]. Parameter 5 about supply chain specificity is set to 10% based on the assumption that data from production sites and key suppliers are specific, and that this data represents 90% of the impact, the remaining 10% being non-specific.

The data quality factors for each parameter are combined into one uncertainty score using Equation (3) describing the uncertainty of the impact potential results provided in the EPDs:

$$Z_{EPD} = \sqrt{Z_M^2 + Z_F^2 + Z_P^2 + Z_T^2 + Z_S^2} \quad (3)$$

where Z_M is the DQ_f for manufacturer specific, Z_F is the DQ_f for facility specific, Z_P is the DQ_f for product specific, Z_T is the DQ_f for time specific, and Z_S is the DQ_f for supply chain specific.

3. Results

3.1. Characteristics of EPDs on Structural Wood

The review paper analyzed 81 EPDs found from the search. The EPDs belong to 11 different EPD program holders. Four of the EPDs contain documentation and results for more than one product. Therefore, a total of 86 products are documented in the EPDs, distributed by the EPD programs as shown in Figure 2. Furthermore, a total of 17 of the EPDs from Environdec and EPD Denmark contain more than one end-of-life (EoL) scenario for the declared product. The total amount of additional product scenarios reported in the EPDs amount to 64 EoL scenarios. The Environdec EPD program holds most of the available EPDs and is also the program where the EPDs contain the higher number of scenarios. This reflects Environdec's broader geographical coverage that spans a range of countries, whereas most of the other programs hold EPDs representing products primarily within the regional or national context of the program.

In total, 16 of the EPD documents, i.e., 20%, were available in a format other than the PDF file format, either as a CSV or XLS format.

Details about the EPDs included in this review can be found in the Supplementary Materials.

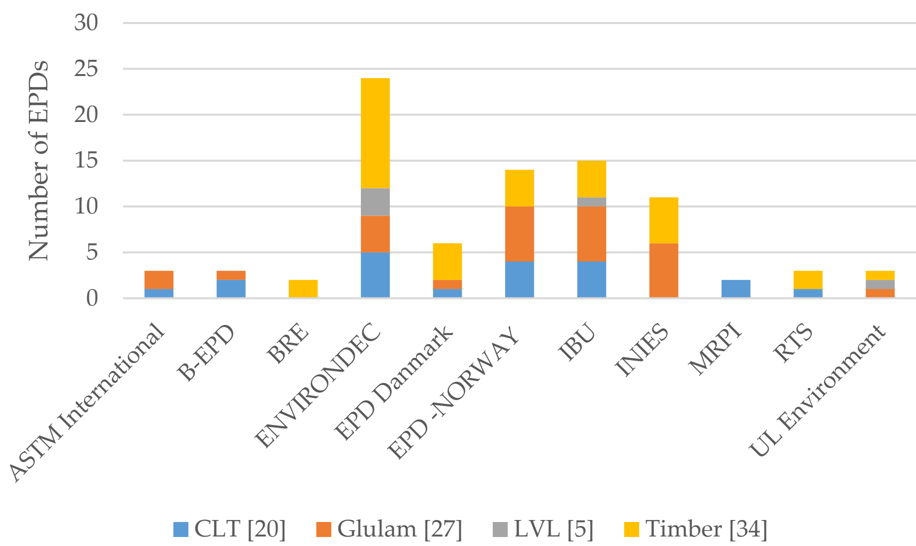

Figure 2. Total number of EN 15804 EPDs on structural wood products [in brackets], distributed on EPD program holders.

3.1.1. Validity of EPDs

The available EPDs were approved in the period 2015–2021. Especially, the period 2018–2020 saw an increase in the number of published EPDs of structural wood products, as seen in Figure 3. In relation to wood products, the reporting of biogenic carbon content and sequestered CO_2 is an important reporting parameter. The EN 15804: A2 version released in 2019 contains an updated list of environmental indicators to report, for instance, concerning the GWP, which will be reported in the details of GWP_{fossil}, $GWP_{biogenic}$, and GWP_{LULUC}. The implementation of the EN 15804: A2 is shown in the EPDs published after publication in 2019.

The validation period of an EN 15804 EPD is 5 years, although several of the EPDs in the sample have had their validation period extended by a revision of the EPD. As seen in Figure 3, a high number of EPDs were published in 2018–2020 based on the EN 15804: A1, and these EPDs will be valid up until 2025. Hence, for several years to come, the available EPDs on structural wood will contain different reporting formats on GWP and other environmental indicators, such as AP and EP.

Apart from the use of EN 15804: A1 and EN 15804: A2 as core PCRs, the majority of the EPDs state that they align with the specific PCRs of their respective program holder. The PCRs may prescribe additional documentation and formatting requirements. An example of additional reporting requirements for biogenic CO_2 is found in the EPD-Norway program, where the PCR in use, even before the EN 15804: A2, required specific documentation of the biogenic CO_2 at different oxidation rates.

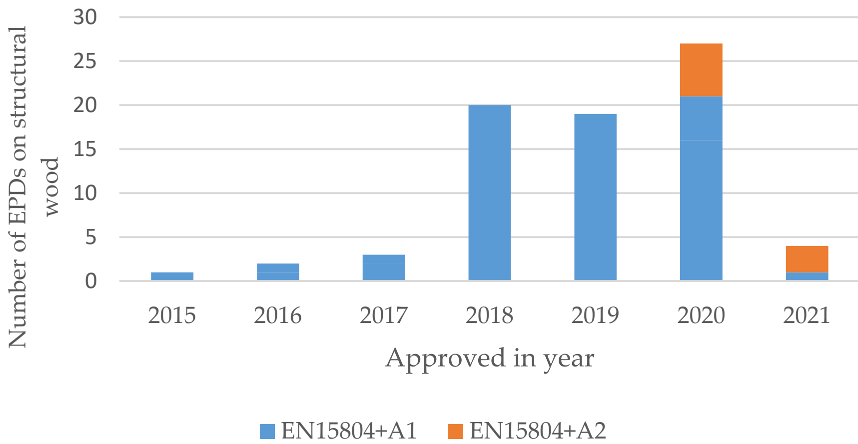

Figure 3. Number of EN 15804 EPDs and their year of approval.

3.1.2. Scope of EPDs

The scope of life cycle stages varies across the sample of EPDs. A total of 14 differently defined scopes of life cycle modules are found in the sample of EPDs. As shown in Figure 4, 18 of the EPDs include a scope where only life cycle modules A1–A3 and potentially A4 are included. The remaining 68 EPDs include some combination of EoL modules C1–C4 as part of the scope.

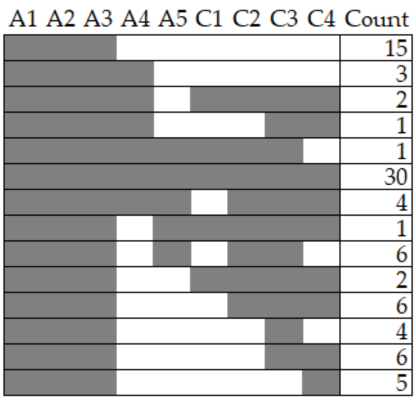

Figure 4. Characterization of included life cycle modules in the sample of EPDs. A total of 14 different types of scopes were found in the overall sample of EPDs.

The 18 EPDs that include only production modules A1–A3 (and potentially A4) often report only the biogenic CO_2 uptake in the structural wood and not the release, leading to unbalanced mass flows. When these unbalanced numbers are applied by EPD users, this can lead to misrepresentations of the actual impact of the product, because the product reports a negative GWP, i.e., it seems like a climate mitigation measure to use the product in question. However, according to the updated standard EN 15804: A2, EoL modules shall be reported. This leads to some degree of mass balancing of the biogenic CO_2, although a chosen EoL scenario of landfilling may still affect the total balancing. This is further explained in Section 3.2.

A total of 71 EPDs report the loads and benefits of the next product system, module D, as part of the scope. The module D scenarios represent a broad range of substitution scenarios covering energy conversion from different sources as well as recycling and reuse scenarios. Module D impacts do not belong to the product system under study but rather the next product system. Because module D, according to the standards, is to be reported separately from the life cycle impacts of a product (to avoid double counting in relation to the next system), the reported numbers from module D were not further investigated in this study.

3.1.3. Geographical Coverage of EPDs

Figure 5 shows a heat map of the country of origin of the 81 structural wood products represented in available EPDs. There is a notable share of European countries with five or more EPDs on structural wood products. Specifically, the countries in which regulation is prepared at the moment (France, Nordic countries) display higher numbers of available EPDs.

Note that language barriers may have prevented collection of EPDs from countries in Asia, Africa, and South and Central America. However, it is likely that there are none, or very few, EN 15804-compatible EPDs from these regions, as the EN 15804 is Eurocentric in its origin from The European Committee for Standardization. Still, the existence of EPDs from Canada, US, Australia, and New Zealand serve to show that the structure and content of the verified EN 15804 EPDs are seen as useful in their own regional contexts.

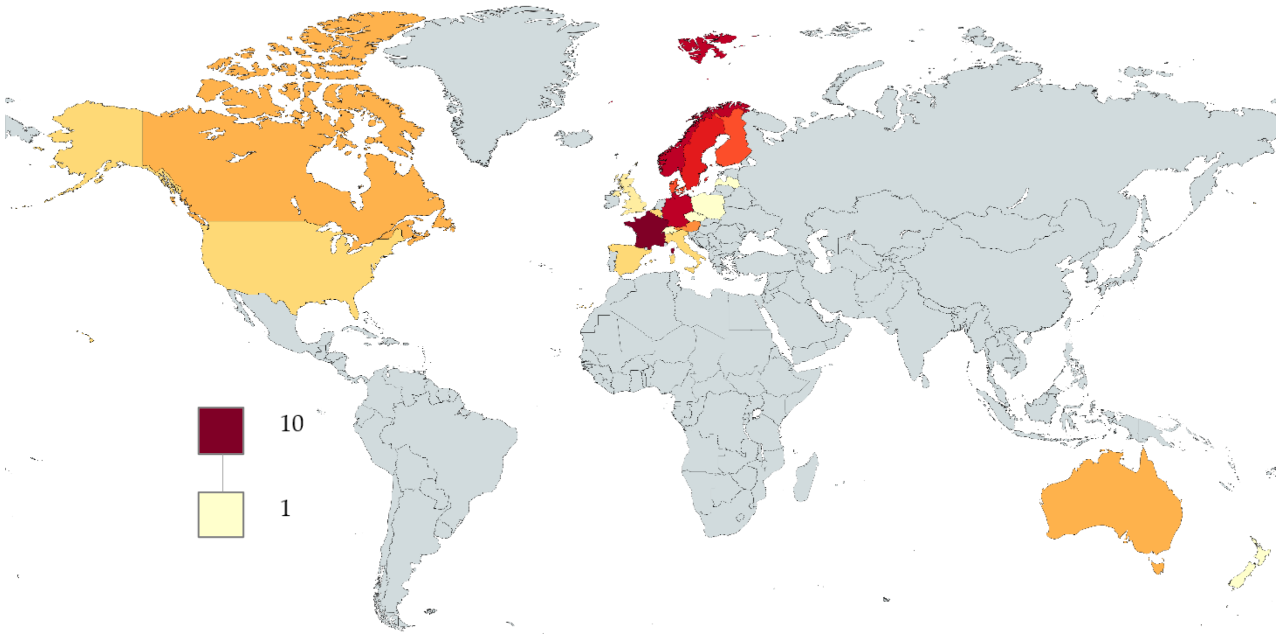

Figure 5. Heat map of the country of origin of the 81 EPDs on structural wood products. Graphic made with mapchart.net.

3.2. Reported Environmental Impacts—GWP

In Figure 6, the reported GWP from production modules (A1–A3), EoL modules (C3–C4), and the total of these are presented in box plots. The upper line of the box is the 75th percentile, and the lower line of the box is the 25th percentile. The median of the data set is denoted with a line in the box. The average is represented by the x. The procedure for selecting and normalizing data for the graph is as follows:

- For A1–A3: All unique products are included, i.e., unique production impacts reported by the EPD sample.
- For C3–C4: All individual scenarios for EoL are included. One unique product may have up to five EoL scenarios
- For A1–A3–C3–C4: All individual scenarios are included, confer C3–C4 above. In cases where only cradle-to-gate impacts are reported, including biogenic CO_2, the biogenic CO_2 is counterbalanced in a manual step based on the reported (or estimated) biogenic CO_2. Details can be found in the methods section about data normalization.

The trend across product categories is that production modules report negative values of CO_2e emissions due to the sequestration of biogenic CO_2 in the tree growth (module A1). As reflected in the C3–C4 numbers, biogenic CO_2 is released at the EoL modules of products. The numbers for total GWP (A1–A3 + C3–C4) amount to median values of approximately 110 kg CO_2e/m^3 for CLT and glulam, and 58 kg CO_2e/m^3 for timber (including both hardwood and softwood). A difference between the totals of the engineered products CLT and glulam and the total of timber is expected, due to the higher density as well as the additional processes and materials associated with the production of CLT and glulam. The LVL sample consists of only four different products spanning 10 scenarios, which is considered too small a sample for deriving statistically based values. The span between the LVL data points is notable, however.

Variations Due to Density and EoL

The variation of the total GWP for glulam and for timber is also notable, especially, where several data points between the minimum and the median fall at values below 0 kg CO_2e/m^3. Hence, even though the median value is at 58 kg CO_2e/m^3 for timber in general, several products present a negative total GWP. These negative GWP numbers are rooted in the EoL scenario definitions applied for the products in the EPD. According to the EN 15804:A2, the biogenic CO_2 sequestered in the wood at growth shall be counterbalanced at the EoL modules. The total counterbalancing of sequestered CO_2 is not always followed, in the sense that released CO_2 from EoL is less than the biogenic CO_2 uptake in the production modules of the life cycle. Several of the EPDs are made according to program-specific PCRs that allow for inclusion of additional EoL scenarios. Specifically, landfill scenarios, where permanent storage of the majority of biogenic CO_2 is assumed, generate negative GWP values. The variation between reported impacts from EoL scenarios in the EPDs is shown in Figure 7a, normalized per kg of structural wood product.

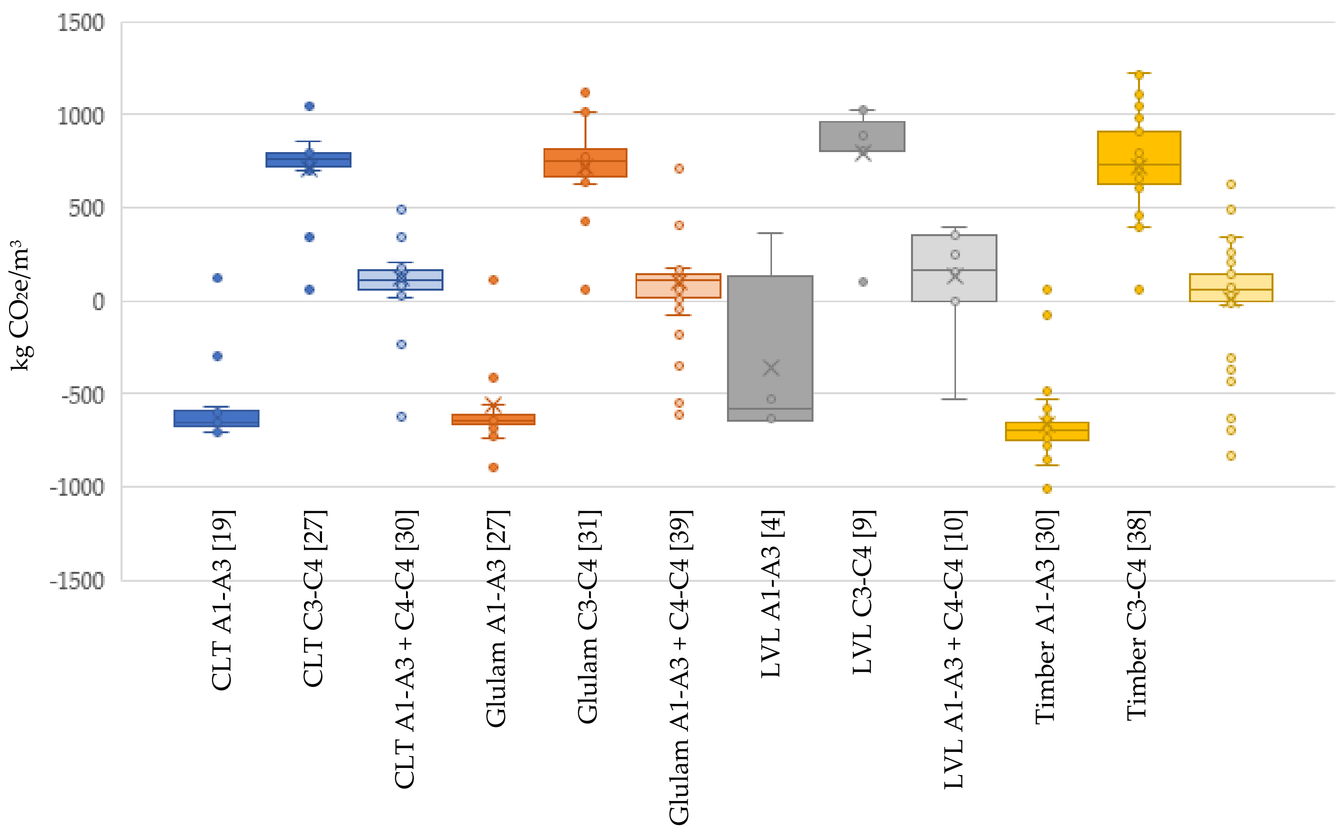

Figure 6. Reported GWP from production (A1–A3), EoL (C3–C4), and total (A1–A3 + C3–C4) from the sample of 81 structural wood product EPDs in accordance with EN 15804. Numbers in brackets indicate the number of data points, i.e., relevant product scenarios included.

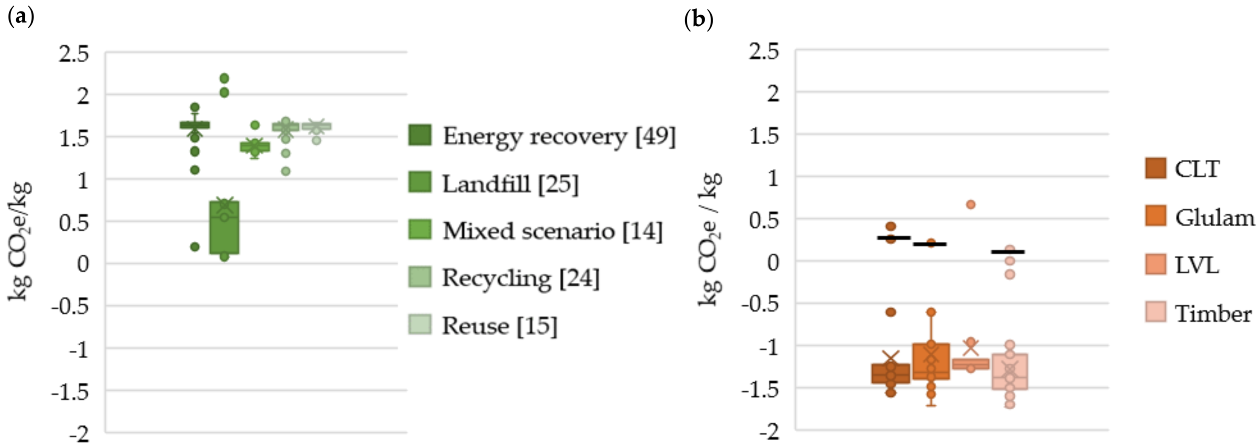

Figure 7. (**a**) Reported GWP in CO_2e from different EoL options applied in the surveyed EPDs, normalized to impacts per kg of product. The numbers in brackets indicate the number of data points, i.e., relevant product scenarios included. (**b**) Reported GWP in CO_2e from the different categories of structural wood in the surveyed EPDs, normalized to impacts per kg of product. Black marks show GWP further normalized to exclude biogenic CO_2.

Figure 7a furthermore illustrates how 14 of the product scenarios use a mixed scenario approach for the EoL modelling. For instance, a declared EoL impact represents a scenario in which 33% is recycled, 16% is incinerated with energy recovery, and 17% is landfilled. These kind of specific mix scenarios seem to be applied to represent national averages of wood waste treatment. However, it makes it difficult to use the EoL of the EPDs in local settings, where another EoL scenario mix may be more representative.

Figure 7b illustrates the reported GWP from A1–A3 of the EPDs, normalized by density. Figure 6 indicates almost a factor 2 difference between GWP timber and CLT/glulam for A1–A3 + C3–C4. However, the difference is reduced drastically when looking at A1–A3 normalized by weight. For CLT, the median is at −1.36 kg CO_2e/kg; for glulam, at −1.31 kg CO_2e/kg; and for timber, at −1.38 kg CO_2e/kg. When further normalized to exclude biogenic CO_2, the median values are at 0.26, 0.24, and 0.17 kg CO_2e for CLT, glulam, and timber, respectively, as shown by the black marks in Figure 7b.

Figure 6andFigure 7a,b thus show that the median values of reported GWP may vary up to a factor 2 between categories of structural wood product, but this difference is largely explained by the density of the products as well as the EoL scenarios applied in the EPDs.

3.3. Reported Environmental Impacts—Other Than GWP

GWP is the more reported impact category in LCA studies and practice. However, in line with the EN 15804 standard, the EPDs also declare a range of other indicators for potential impacts and resource uses. Figure 8a–e show the correlation between GWP from A1–A3 and a selection of additional impacts and resource uses, all normalized to one kilogram of wood. The R2 values for the correlation between GWP and acidification potential AP (a), eutrophication potential (EP) (b), and primary energy, non-renewable, total PENRT (d) indicate a fit to the trend line between 9% and 18%, which cannot be characterized as a strong fit to the correlation model. The bad fittings to models imply that the use of GWP as a single point of reference is not appropriate to capture equivalent potentials in these other impact and resource use categories. In the case of abiotic depletion potential for elements ADPE (e), the sample is characterized by large variations within the reported results, spanning from a minimum of 4.9×10^{-9} kg Sb-e/kg to a maximum of 2.7×10^{-5} kg Sb-e/kg.

The use of primary energy, renewable, and total PERT (c) covers not only the renewable energy used for processes along the life cycle modules, e.g., wood chips for kiln drying, but also integrates the renewable feedstock energy embodied in the product. This feedstock energy is balanced in the life cycle of the product, like the biogenic CO_2, albeit with a reverse sign. Hence, it is typically accounted for as a resource use in the A1 module and counterbalanced in the C3 or C4 module. The balancing of the feedstock energy is found around the lower heating value of dry wood, which is around 19 MJ/kg wood.

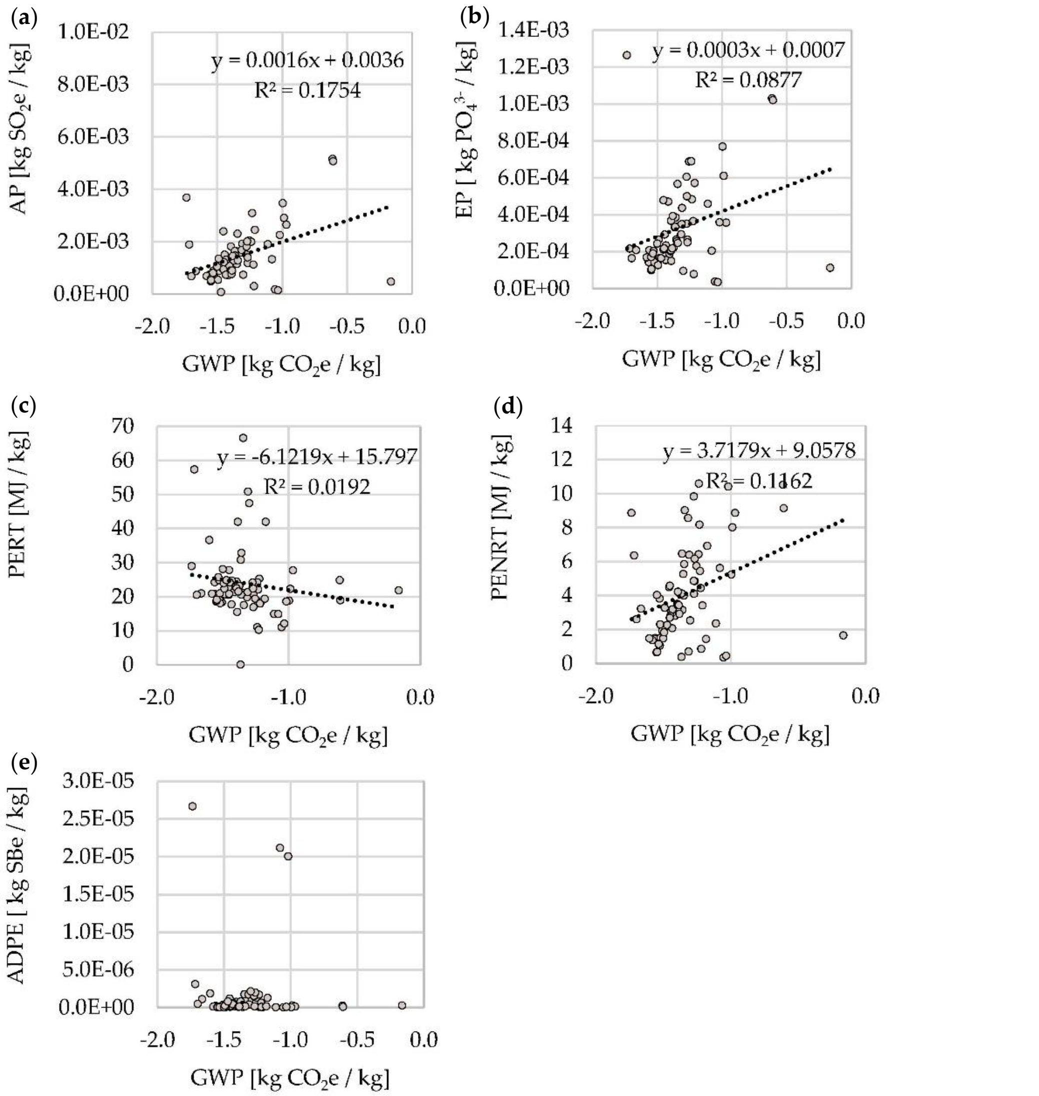

Figure 8. (**a**) Correlation between GWP and AP for life cycle modules A1–A3. (**b**) Correlation between GWP and EP for life cycle modules A1–A3. (**c**) Correlation between GWP and PERT for life cycle modules A1–A3. (**d**) Correlation between GWP and PENRT for life cycle modules A1–A3. (**e**) Correlation between GWP and ADPE for life cycle modules A1–A3.

3.4. Uncertainty Assessment of EPD Sample

The sample of EPDs represent varying degrees of specificity in terms of manufacturer, facility, co-production, time of data representation, and supply chain. The uncertainty of the EPD sample is assessed with the method by Waldman et al., 2020, as described in the method section. Figure 9 shows the distribution between the different categories that the EPDs fall in, depending on the specificity. As seen in the figure, the majority of CLT EPDs represent a single manufacturer, at a single production site, producing only one product. In total, 45% of all EPDs in the sample are of this degree of specificity. At the other end of the scale, 46% of all EPDs in the sample represent various manufacturers, at various production sites. This lower degree of specificity dominates the collection of timber EPDs.

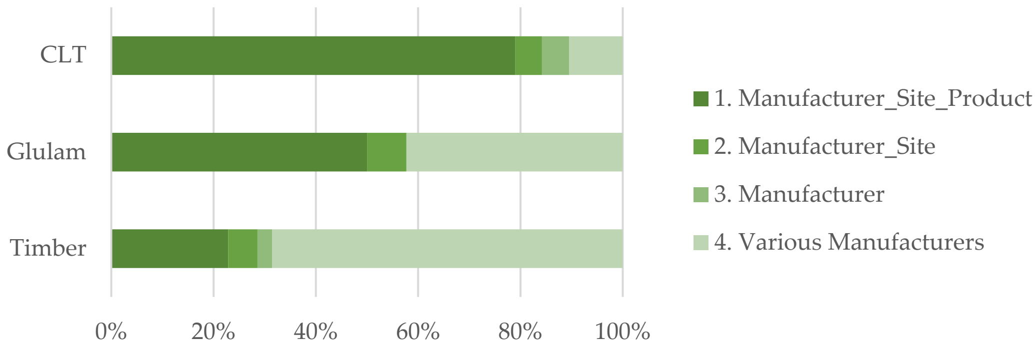

Figure 9. Specificity of EPDs in the areas of manufacturer, facility, and co-production, presented as category 1–4.

Calculating the uncertainty of the EPDs (the $\pm Z_{EPD}$), values to represent the specificity degrees are found as ±21%, ±30%, ±36%, and ±41% for category 1, 2, 3, and 4, respectively. According to Waldman et al., these Z_{EPD} factors are added to the reported results to "... *form the bounds of reasonable confidence, meaning that it is reasonably likely that any given specific instance of a product (e.g., a specific kg of rebar) in the population (i.e., all the products represented by the EPD) will have a value within that range*." [39]. Using timber as an example, the factors for individual EPDs were added to the reported GWP and are shown in Figure 10. Note that the GWP numbers are adjusted for biogenic CO_2 content, since this follows the mass and hence should not be affected by uncertainty in the same way as other processes contributing to GWP.

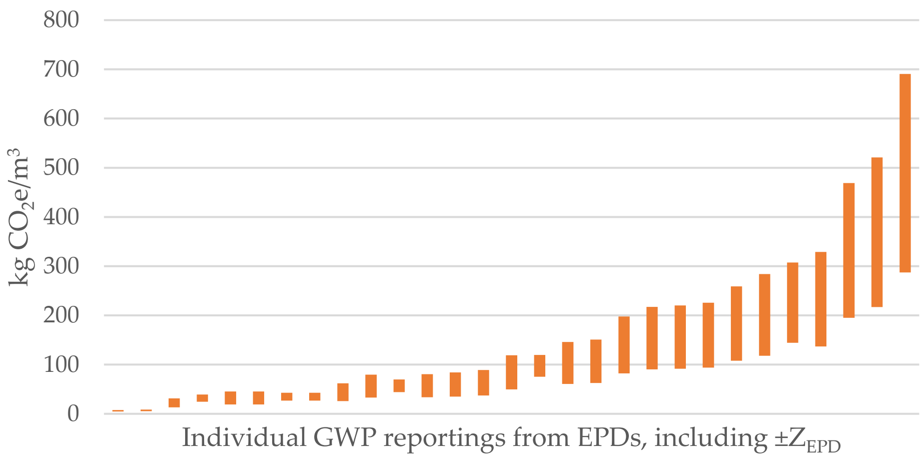

Figure 10. Uncertainty span added to the reported production stage GWP (A1–A3) of timber products. Numbers are adjusted for reported or estimated biogenic CO_2 content.

The nature of the $\pm Z_{EPD}$ calculation means that higher-end results are more affected in an absolute sense. For instance, the latter value in Figure 10 has a calculated uncertainty span of ±41% and thus spans from 287–691 kg CO_2e/m^3. This may come across as a suspiciously large span, leading to questioning of the method behind the $\pm Z_{EPD}$. However, the specific EPD in question, an EPD of Australian hardwood, is transparent in its own reporting of variations between the 33 manufacturers behind the EPD. Hence, variations between −42% and +90% are reported for the kiln-dried hardwood. This shows that the uncertainty of EPDs is not to be neglected when numbers from EPDs are used further, for instance in building design evaluations.

4. Discussion

4.1. Implications for Use and Development of EPDs

EPDs are intended for use in the decision-making concerning building design and material choice. This study mapped the availability and characteristics of EPD data, and points to some areas of attention for the uptake, use, and development of EPD data in the building industry.

The mapping shows a high concentration of EPDs in the European countries, especially covering the countries where regulation is on the political agenda. This indicates how industry in those countries is preparing for an increased demand for product data to support decision-making in the building design process.

Recent research and practice highlight the necessity of digitalization in the design process [44,45], and it is thus imperative that EPD data becomes available in digital formats that support a digitalized work processes. At the current state, only 20% of the EPDs on structural wood are available in digital formats other than pdf.

The use of representative data is a key concern in building-LCA, and the vast amount of available EPD data thus require that EPD users critically assess the data they apply, increasing the workload dramatically. Depending on the building design stage, it may be appropriate to use generic data or it may be appropriate to use product-specific data. However, in their current forms, it can be difficult to assess the representativeness of data because documentation varies hugely, not only between EPD program holders, but sometimes also between EPDs in the same program. For the sake of the EPD users, EPD programs should consider harmonizing documentation requirements to ensure transparency at the highest level possible.

4.2. Comparison with Database Values

Building-LCA practitioners in search for data have the option of using one of the publicly available databases for construction materials provided by companies, research institutions, or governmental bodies. Examples of these available databases include ICE from the UK [46], KBOB from Switzerland [47], and Ökobaudat from Germany [48]. In connection with the ongoing regulatory development in Sweden, a national database, the Klimatdatabas [49], is also in its testing phase. These databases have in common that they offer building-LCA practitioners data covering a large range of construction materials. The databases provide generic and/or average data, and Ökobau also contains digitalized EPDs for specific products.

A comparison of the median values from the current study with generic GWP values found in the databases provide an overview as shown in Figure 11. The median values derived from the EPDs are displayed for modules A1–A3 and normalized to kg of product without biogenic CO_2. As seen in Figure 11, the EPD medians are, for all product categories, in the lower end of the scale. This is expected, since the publicly available databases for construction products, in general, choose to display conservative values for the generic data. A similar pattern was found by Hill and Dibdiakova in a comparison of wood product EPDs with values from the ICE database [50].

The median GWP values found in this study are based on a broad sample of EPDs for structural wood products. Hence, median values may be used by building-LCA practitioners in cases where no regional generic data exist, or the values may be used for LCA screenings early in the building design, where specific products are not yet decided upon. The large spans within the categories (see Figure 6) and the uncertainties of the EPDs (see Figure 10) should, however, be kept in mind.

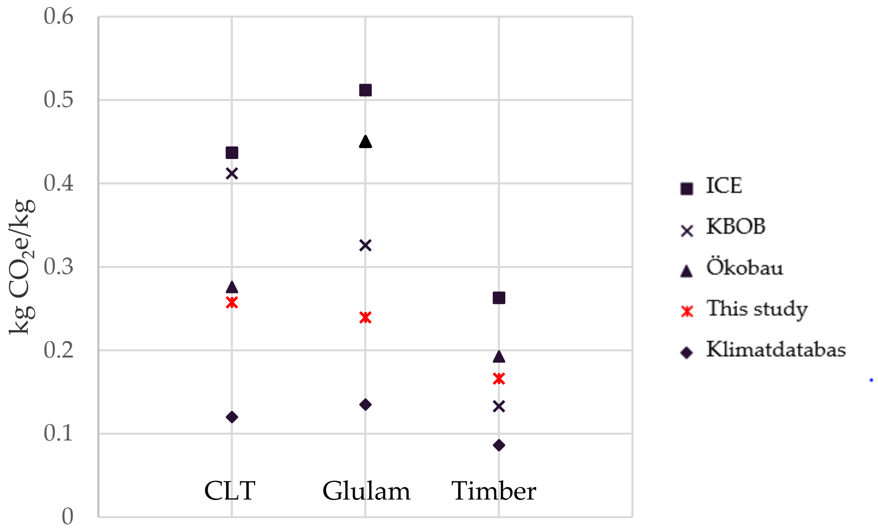

Figure 11. A1–A3 GWP values per kg of wood product (without biogenic CO_2) from the current study and as reported in publicly available databases for construction products.

4.3. Potential Pitfalls in the Use of EPDs

The comparison of GWP and other environmental impacts reported from EPDs showed notable variations between the different product categories at a comparative basis of 1 m^3, but less variation at a comparative basis of 1 kg. The density and the EoL scenarios were shown to be key factors in determining the total GWP. EPD users thus need to be specifically aware of these factors when determining whether an EPD may be seen as representative.

Although GWP is receiving special attention by the building industry, results from this study also show that EPD users should be cautious in seeing GWP as an indicator for the products' overall environmental performance. The weak correlation between GWP and several other indicators is a specific point of attention for EPD users working under multiple LCA criteria, for instance via certification systems for sustainable buildings.

The embedded uncertainty in reported EPD impacts is an additional point of attention for the EPD users. One level of uncertainty pertains to the specificity of data, as investigated in this study by use of the Z_{EPD} method, i.e., how representative is the data in terms of time and place to the actual product considered for use. An additional level of uncertainty pertains to the methodological approaches applied by the EPD producers, in the cases where the EN 15804 standard is not specific, leaving room for interpretation. This is, for instance, the case of allocation of impacts between the main product and by-products [51] and for choosing scenarios for modules C and D [52]. Both levels of uncertainty should be recognized, and preferably integrated in further use of the numbers.

4.4. Limitations of Study

This study is a review of EPD data, which is a rapidly changing field of industry activity. The validity of an EPD is five years, so the EPD data form a a dynamic pool of material data. Hence, this study may be seen as a snapshot of a field of data in development. In a future with digitized EPDs, the review exercise of this study may be conducted less laboriously, and the results and values be subject to regular updates.

The main limitation of the study is found in the sometimes diverging approaches to calculating and reporting results in the EPDs. Even though all included EPDs are in line with the EN 15804 standard, the varying program-specific PCRs result in numbers that may be difficult to compare. For instance, the PCR from UL Environment guides calculations based on the Traci characterization method [53]. For GWP, this means a difference to the CML characterization method because they build on different assessment reports from the International Panel of Climate Change IPCC. The differences in GWP from the two methods are considered negligible [54] but may nevertheless be considered a bias to results. Likewise, the different ways of reporting GWP from the EN 15804:A1 and the GWP_{total} in EN 15804:A2 are considered to have a minor effect on the comparability [54].

5. Conclusions

This study provides a comprehensive review of 81 third-party verified EPDs of structural timber, identified as complying with EN 15804. The 81 EPDs represent 86 different products and 152 different product scenarios. The EPDs mainly represent European production, but North America and Australia/New Zealand productions are also represented. More than 80% of EPDs include a more complete life cycle with EoL options, and this number will grow in the transition from versions EN 15804: A1 to EN 15804:A2.

Reported GWP from the EPDs vary broadly within each of the investigated categories of CLT, glulam, LVL, and timber. The variations were shown to be closely related to the density of the products and the EoL scenarios applied. When normalizing the results per kg of product, and further excluding the biogenic CO_2, median values of 0.26, 0.24, and 0.17 kg CO_2e were found for CLT, glulam, and timber, respectively.

The results further showed that the correlation between GWP and other impact categories is limited, and that the inherent data uncertainty may add up to ±41% to reported impacts when assessed with an uncertainty method from the literature. In the EPDs, uncertainties of up to 90% for GWP are reported as an example.

Building-LCA practitioners can use the median values from this study as generic data in their assessments of buildings. To make the EPDs easier to use for practitioners, a more detailed coordination between EPD program holders is recommended, as well as the development of digitalized EPD data.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/buildings11080362/s1, Table S1: Overview of EPDs included in study.

Author Contributions: Conceptualization F.N.R., C.E.A. and A.W.; methodology, F.N.R. and C.E.A.; investigation, C.E.A., F.N.R., A.W. and R.N.H.; data curation, C.E.A. and F.N.R.; writing—original draft preparation, F.N.R. and C.E.A.; writing—review and editing, A.W., R.N.H. and H.B.; funding acquisition, H.B. and F.N.R. All authors have read and agreed to the published version of the manuscript.

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References

1. International Energy Agency; Global Alliance for Buildings and Construction. *2019 Global Status Report for Buildings and Constructi on Towards a Zero-Emissions, Efficient and Resilient Buildings and Constructi on Sector*; United Nations Environment Programme: Nairobi, Kenya, 2019; ISBN 9789280737684.
2. IEA. *Material Efficiency in Clean Energy Transitions*; IEA Publications: Paris, France, 2019. [CrossRef]
3. Hertwich, E.; Lifset, R.; Pauliuk, S.; Heeren, N. *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future*; United Nations Environment Programme: Nairobi, Kenya, 2020. [CrossRef]
4. Hertwich, E.G.; Ali, S.; Ciacci, L.; Fishman, T.; Heeren, N.; Masanet, E.; Asghari, F.N.; Olivetti, E.; Pauliuk, S.; Tu, Q.; et al. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—A review. *Environ. Res. Lett.* **2019**, *14*, 4. [CrossRef]
5. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Appl. Energy* **2019**, *258*, 114107. [CrossRef]
6. Frischknecht, R.; Birgisdottir, H.; Chae, C.U.; Lützkendorf, T.; Passer, A. IEA EBC Annex 72—Assessing life cycle related environmental impacts caused by buildings—Targets and tasks. *IOP Conf. Series Earth Environ. Sci.* **2019**, *323*, 012042. [CrossRef]
7. Lützkendorf, T. Assessing the environmental performance of buildings: Trends, lessons and tensions. *Build. Res. Inf.* **2017**, *3218*, 1–21. [CrossRef]
8. Kuittinen, M.; Häkkinen, T. Reduced carbon footprints of buildings: New Finnish standards and assessments. *Build. Cities* **2020**, *1*, 182–197. [CrossRef]

9. Boverket. Miljö-och Klimatanpassade Byggregler; Karlskrona. 2016. Available online: https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2016/miljo--och-klimatanpassade-byggregler (accessed on 3 April 2021).
10. Ministry of Business, Innovation & Employment. Whole-of-Life Embodied Carbon Emissions Reduction Framework—Building for Climate Change Programme. 2020. Available online: www.mbie.govt.nz (accessed on 12 July 2021).
11. Francart, N.; Larsson, M.; Malmqvist, T.; Erlandsson, M.; Florell, J. Requirements set by Swedish municipalities to promote construction with low climate change impact. *J. Clean. Prod.* **2018**, *208*, 117–131. [CrossRef]
12. Rasmussen, F.N.; Birkved, M.; Birgisdóttir, H. Low-carbon design strategies for new residential buildings—lessons from architectural practice. *Arch. Eng. Des. Manag.* **2020**, *16*, 374–390. [CrossRef]
13. Nußholz, J.L.; Rasmussen, F.N.; Whalen, K.; Plepys, A. Material reuse in buildings: Implications of a circular business model for sustainable value creation. *J. Clean. Prod.* **2019**, *245*, 118546. [CrossRef]
14. D'Amico, B.; Pomponi, F.; Hart, J. Global potential for material substitution in building construction: The case of cross laminated timber. *J. Clean. Prod.* **2020**, *279*, 123487. [CrossRef]
15. Hildebrandt, J.; Hagemann, N.; Thrän, D. The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustain. Cities Soc.* **2017**, *34*, 405–418. [CrossRef]
16. Göswein, V.; Reichmann, J.; Habert, G.; Pittau, F. Land availability in Europe for a radical shift toward bio-based construction. *Sustain. Cities Soc.* **2021**, *70*, 102929. [CrossRef]
17. Ramage, M.H.; Burridge, H.; Busse-Wicher, M.; Fereday, G.; Reynolds, T.; Shah, D.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; et al. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev.* **2017**, *68*, 333–359. [CrossRef]
18. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]
19. Hoxha, E.; Passer, A.; Saade, M.R.M.; Trigaux, D.; Shuttleworth, A.; Pittau, F.; Allacker, K.; Habert, G. Biogenic carbon in buildings: A critical overview of LCA methods. *Build. Cities* **2020**, *1*, 504–524. [CrossRef]
20. Andersen, C.E.; Rasmussen, F.N.; Habert, G.; Birgisdóttir, H. Embodied GHG emissions of wooden buildings—Challenges of biogenic carbon accounting in current LCA methods. *Front. Built Environ.* **2021**, in press.
21. Rasmussen, F.N.; Malmqvist, T.; Birgisdóttir, H. Drivers, barriers and development needs for LCA in the Nordic building sector-a survey among professionals Drivers, barriers and development needs for LCA in the Nordic building sector-a survey among professionals. *IOP Conf. Series Earth Environ. Sci.* **2020**, *588*, 032022. [CrossRef]
22. Balouktsi, M.; Lützkendorf, T.; Röck, M.; Passer, A.; Reisinger, T.; Frischknecht, R. Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72. *IOP Conf. Series Earth Environ. Sci.* **2020**, *588*, 032023. [CrossRef]
23. Pomponi, F.; Moncaster, A. Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2431–2442. [CrossRef]
24. Mengarelli, M.; Neugebauer, S.; Finkbeiner, M.; Germani, M.; Buttol, P.; Reale, F. End-of-life modelling in life cycle assessment—material or product-centred perspective? *Int. J. Life Cycle Assess.* **2016**, *22*, 1288–1301. [CrossRef]
25. Frischknecht, R.; Althaus, H.J.; Bauer, C.; Doka, G.; Heck, T.; Jungbluth, N.; Nemecek, T. The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. *Int. J. Life Cycle Assess.* **2007**, *12*, 7–17. [CrossRef]
26. Martínez-Rocamora, A.; Solís-Guzmán, J.; Marrero, M. LCA databases focused on construction materials: A review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 565–573. [CrossRef]
27. Dixit, M.; Culp, C.H.; Fernández-Solís, J.L. System boundary for embodied energy in buildings: A conceptual model for definition. *Renew. Sustain. Energy Rev.* **2013**, *21*, 153–164. [CrossRef]
28. Rasmussen, F.N.; Malmqvist, T.; Moncaster, A.; Wiberg, A.H.; Birgisdottir, H. Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. *Energy Build.* **2018**, *158*, 1487–1498. [CrossRef]
29. EN ISO 14025. *Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures*; International Organization for Standardization: Geneva, Switzerland, 2006.
30. Gelowitz, M.; McArthur, J. Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation. *J. Clean. Prod.* **2017**, *157*, 125–133. [CrossRef]
31. Ingwersen, W.; Stevenson, M.J. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. *J. Clean. Prod.* **2012**, *24*, 102–108. [CrossRef]
32. *CEN. EN 15804:2013+A1—Sustainability of Constructions Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products*; British Standards Institution: London, UK, 2012.
33. Passer, A.; Lasvaux, S.; Allacker, K.; De Lathauwer, D.; Spirinckx, C.; Wittstock, B.; Kellenberger, D.; Gschösser, F.; Wall, J.; Wallbaum, H. Environmental product declarations entering the building sector: Critical reflections based on 5 to 10 years experience in different European countries. *Int. J. Life Cycle Assess.* **2015**, *20*, 1199–1212. [CrossRef]
34. Gantner, J.; Lenz, K.; Horn, R.; Von Both, P.; Ebertshäuser, S. Ökobau.dat 3.0–Quo Vadis? *Buildings* **2018**, *8*, 129. [CrossRef]
35. Herrero-Garcia, V. Whole-Building Life Cycle Assessment: Comparison of Available Tools. *Technol. Des.* **2020**, *4*, 248–252. [CrossRef]
36. Hill, C.; Norton, A.; Dibdiakova, J. A comparison of the environmental impacts of different categories of insulation materials. *Energy Build.* **2018**, *162*, 12–20. [CrossRef]

37. Welling, S.; Ryding, S.-O. Distribution of environmental performance in life cycle assessments—Implications for environmental benchmarking. *Int. J. Life Cycle Assess.* **2021**, *26*, 275–289. [CrossRef]
38. Anderson, J.; Moncaster, A. Embodied carbon of concrete in buildings, Part 1: Analysis of published EPD. *Build. Cities* **2020**, *1*, 198–217. [CrossRef]
39. Waldman, B.; Huang, M.; Simonen, K. Embodied carbon in construction materials: A framework for quantifying data quality in EPDs. *Build. Cities* **2020**, *1*, 625–636. [CrossRef]
40. Božiček, D.; Kunič, R.; Košir, M. Interpreting environmental impacts in building design: Application of a comparative assertion method in the context of the EPD scheme for building products. *J. Clean. Prod.* **2020**, *279*, 123399. [CrossRef]
41. *CEN. EN 15804:2012+A2:2019—Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products*; British Standards Institution: London, UK, 2019.
42. Anderson, J. ConstructionLCA's 2021 Guide to Environmental Product Declarations (EPD). *ECO PLATFORM AISBL*. 2021. Available online: https://www.eco-platform.org/epd-facts-figures.html (accessed on 8 April 2021).
43. Dias, A.; Silvestre, J.; de Brito, J. Comparison of the environmental and structural performance of solid and glued laminated timber products based on EPDs. *Structures* **2020**, *26*, 128–138. [CrossRef]
44. Zimmermann, R.; Bruhn, S.; Birgisdóttir, H. BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs. *Sustainability* **2021**, *13*, 5455. [CrossRef]
45. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
46. Circular Ecology. Embodied Carbon—The ICE Database. *Circ. Ecol.* 2020. Available online: https://circularecology.com/embodied-carbon-footprint-database.html (accessed on 3 April 2021).
47. Plattform Ökobilanzdaten im Baubereich. Available online: https://www.kbob.admin.ch/kbob/de/home/die-kbob/plattform-oekobilanzdaten-im-baubereich.html (accessed on 12 July 2021).
48. ÖKOBAUDAT. Available online: https://www.oekobaudat.de/en.html (accessed on 12 July 2021).
49. Boverkets Klimatdatabas-Boverket. Available online: https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/klimatdatabas/ (accessed on 12 July 2021).
50. Hill, C.A.S.; Dibdiakova, J. The environmental impact of wood compared to other building materials. *Int. Wood Prod. J.* **2016**, *7*, 215–219. [CrossRef]
51. Lauri, L.; Roope, H.; Atsushi, T.; Tuovi, V.; Olli, D. Environmental product declaration of timber products: The impact of allocation method to the impact categories. *J. Clean. Prod.* **2020**, *256*, 120386. [CrossRef]
52. Tellnes, L.G.F.; Rønning, A.R. Modelling options for module C and D: Experiences from 50 EPD for wood-based products in Norway. *IOP Conf. Series Earth Environ. Sci.* **2019**, *323*, 012052. [CrossRef]
53. Bare, J. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technol. Environ. Policy* **2011**, *13*, 687–696. [CrossRef]
54. EPD International. *Product Category Rules—Construction Products 2019:14 VERSION 1.11*; The International EPD System: Stockholm, Sweden, 2019.