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LCA COMMUNICATION AND LCA FOR ISO LABELS

Same product, different score: how methodological differences affect EPD results

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Abstract

Purpose Demand for Environmental Product Declarations (EPDs) is already high and increasing in the construction and building sectors. The overall purpose of EPDs is comparability of product environmental performance, and they are thus developed in accordance with product category rules (PCRs): requirements and guidelines for how to make EPDs for one or more product groups. Since several organisations publish PCRs, there is a risk of creating conflicting rules leading to inconsistencies and jeopardising the objective of comparability.

Methods This study analyses the causes for inconsistency and the consequences in terms of difference in the results across the life cycle assessment (LCA) models underlying the EPDs. Taking four EPD programmes and their actors as cases, first a document analysis was conducted to identify qualitative and quantitative differences in their guidelines. Further focusing on selected quantitative differences, a series of LCA models were designed for the same triple-glazed window product by adhering to the PCRs of each operator, to highlight the differences in results that occur when performing the same assessment via different but all formally selectable operators and compliant EPDs.

Results and discussion Results show that the EPD of a specific product can return very different impact scores if one or the other guideline is followed. Results can vary more than 10% from the base scenarios, what we consider a significant variation. This is observed across all impact categories. Focusing specifically on the climate change impact, the results show that differences are due to the choice of energy mix, reference service life and other parameters. It is thus the combination of several modelling differences that leads to a overall divergence in results, rather than one single methodological choice.

Conclusions Numerous different but at the same time compliant EPDs can be obtained for the same product, highlighting a serious harmonisation issue within the EPD system. EPDs are thus not necessarily accurate, and it remains doubtful whether EPD comparability can be achieved. This weakness of the EPD system can in the worst case be exploited by producers to obtain lower results and undermines the system.

Recommendations Besides recommending using LCA for learning and process improvement rather than just for external communication and compliance, to increase harmonisation in the EPD system, we recommend limiting the number of product-specific PCRs (e.g. complementary PCRs), align default values, learn from verification, use just one background database, increase transparency and move towards one centralized operator.

Keywords Construction sector · ISO 14025 · EN 15804 · Buildings · Comparative assessment · ISO 21930 · LCA harmonisation · Product-specific LCA

1 Introduction

Environmental Product Declarations (EPDs) are defined by ISO 14025 as documents that present third-party verified environmental information for a product based on the results of the life cycle assessment (LCA) of such product (ISO 2010). Currently, the use of EPDs is particularly widespread in the buildings and construction sector where they are prepared for construction materials and components (Welling

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and Ryding 2021) and used in the assessment of the whole environmental performance of buildings (CEN 2012).

Comparability of EPDs is essential to encourage the demand for products which perform better environmentally and thereby to stimulate environmental improvement, thus achieving the overall purpose of the EPD system. To achieve comparable EPDs, the declarations are developed in accordance with product category rules (PCRs), a set of rules published by programme operators defining how to make EPDs for one or more product categories (ISO 2010). ISO 14025 is the primary standard for EPDs that establishes the procedure for developing PCRs. It includes the required content of a PCR, as well as requirements for comparability (ISO 2010). In Europe, a core PCR (EN 15804) has been developed for construction products (CEN 2013, 2019) with the aim of aligning the rules for EPD development. Two editions of EN 15804 are available: EN 15804+A1 and EN 15804+A2. In 2013, EN 15804+A1 was developed to harmonise the development of PCRs for European construction materials (Gelowitz and McArthur 2017), while EN15804+A2 was developed in 2019 to align construction EPDs with the Product Environmental Footprint (PEF) initiative of the European Commission. The International Organisation for Standardisation (ISO) has published another core PCR, ISO 21930, which is similar to EN 15804+A1 with a few exceptions (ISO 2017). In this document, we refer to the "three core PCRs" as EN 15804+A1, EN 15804+A2 and ISO 21930.

Programme operators are the independent agencies responsible for the implementation of the EPD system within a specific area. There are at least 18 programme operators in Europe, most of them situated in a specific country, for example, the *Institute for Building and Environment "Institut Bauen und Umwelt e.V"* (IBU) in Germany, *EPD International* in Sweden, *EPD Denmark* in Denmark and *EPD Norway* in Norway (ECO Platform 2022). ISO 14025 states that programme operators must have a rule set called General Programme Instructions (GPI) (ISO 2010) where the geographical scope and additional rules and guidelines for EPD development must be specified. Certain programme operators have developed their own PCRs—often called "PCR Part A"—which allegedly outline calculation rules in compliance with one or more of the three core PCRs (EPD Norway 2021; IBU 2021a). Occasionally, core PCRs can be supplemented by a complementary PCR (c-PCR), also called "sub-PCR" or "Part B PCR", providing additional rules and guidelines for a specific group of products like specific construction materials (CEN 2019). For example, the European Committee for Standardisation (CEN) has developed c-PCRs for wood-based products and cement and concrete products (CEN 2014, 2017a, b). Programme operators issue both PCRs and c-PCRs independently. The fact that programme operators often issue rule sets independently has caused inconsistencies in the development of EPDs for the same product materials (Gelowitz and McArthur 2017). The structure of the standards and related PCRs to develop EPDs is given in Fig. 1.

The number of rule sets and their independent development have raised concerns of lack of harmonisation and overlapping rules for similar product categories, thus weakening the comparability of EPDs and preventing the EPD system to function as intended materials (Gelowitz and McArthur 2017).

Lack of harmonisation within EPD schemes was identified already a decade ago (Bogeskär et al. 2002), and several initiatives have tried to overcome the challenge (Del Borghi 2012; Lasvaux et al. 2014). According to Gelowitz and McArthur (2017), EN 15804+A1 has been successful to some degree, as PCRs following this standard perform noticeably better than non-harmonised PCRs based on the comparison of EPDs for three different product categories—insulation, flooring and cladding—and their underlying PCRs. Yet, they find that 3–12% of the EPDs are incomparable even though they have the same PCR, and 73–87% of the EPDs are incomparable with different PCRs of the same product, underlining the need for further development of EN 15804+A1 and similar standards. Almeida et al. (2015) highlight the need for complementary product category rules (c-PCR) to provide specific rules for sub-categories of construction materials, while these rule sets also must be aligned on an international level to achieve harmonisation and guarantee EPD comparability.

Subramanian et al. (2012) and AzariJafari et al. (2021) identify that a main cause for lack of harmonisation is the fact that PCRs are published by different programme operators. Twenty-five percent of programme operators are not compliant with ISO 14025 (Minkov et al. 2015). Gelowitz and McArthur (2017) also find that 78–85% of the EPDs for insulation, flooring and cladding are not compliant with ISO 14025 because they lack some of the required information. For example, some have incomplete system boundary definitions and do not mention or use primary data for their foreground processes. Papadopoulou et al. (2021) identified different rules for the verification processes when comparing the general programme instructions of EPD International and EPD Norway, further suggesting that it may therefore be relevant to investigate if there are other differences in these instructions which prevent harmonisation within the EPD system.

The different geographical scope of programme operators also hinders harmonisation (Minkov et al. 2015). Ingwersen and Stevenson (2012) advocate for PCRs ideally being global in scope, while allowing for regional differences in technology, supply chains and available data, while being defined in accordance with a common classification system to avoid overlapping category boundaries. While most programme operators claim to have international coverage, this is not implemented in practice, and operators tend to

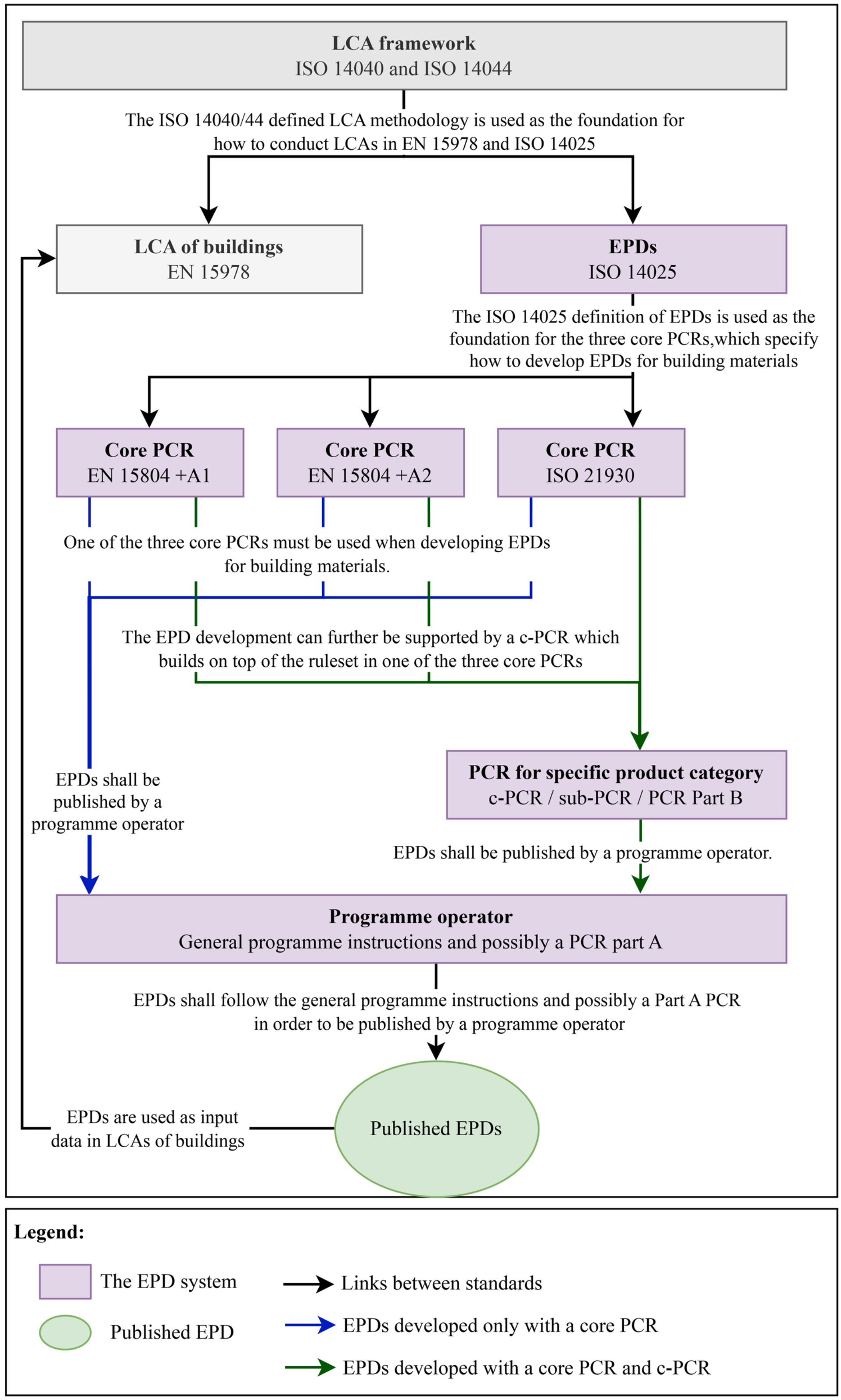

Fig. 1 Standards used for the development of EPDs for construction materials in Europe

narrow the geographical scope of PCRs to consider local supply chains and waste treatment conditions (Anderson et al. 2019). Moreover, both EPDs and PCRs are often published in local languages (Hunsager et al. 2014; Minkov et al. 2015; Toniolo et al. 2019), making it difficult to assess the level of harmonisation.

Excessive room for interpretation of definitions and vocabulary is another reason for lack of harmonisation of EPDs (Minkov et al. 2015; Achenbach et al. 2016; Anderson et al. 2019). Achenbach et al. (2016) report this issue when accounting of primary energy of secondary resources for wood-based products in EN 15804+A1 and the CEN c-PCR, EN 16485. Anderson et al. (2019) exhibit four different ways of reporting the end-of-life and module D in EPDs and conclude that this is caused by the lack of and/or different guidelines in PCRs. Furthermore, Minkov et al. (2015) state that the excessive room for interpretation in PCRs could weaken the comparability of EPDs based on the same PCRs highlighting that differences in methodology and poorly described instructions can lead to competitive favours and inaccurate results.

Finally, specific LCA modelling issues can prevent comparability across EPDs. Ingwersen and Stevenson (2012) and AzariJafari et al. (2021) show how poor inventory data and the lack of common inventory databases can affect the reliability and comparability of EPDs. Gelowitz and McArthur (2017) report that differences in choice of functional unit, cut-off rules and system boundary lead to incomparable EPDs. Lauri et al. (2020) conclude that the choice of allocation methods allowed by EN 15804+A1 and the CEN c-PCR EN 16485 had an effect of 2–33% on the environmental results for timber products depending on the impact category. One can thus make a LCA model that purposefully present a product in the most favourable way, while still being PCR-compliant (Minkov et al. 2015).

The harmonisation of the EPD system should in principle reduce "*the diversity of approaches to modelling product systems found in LCA*" (Ingwersen and Stevenson 2012). Yet, as shown above, harmonisation of rules is still a challenge, and the introduction of core PCRs and c-PCRs has not solved the issue. One may therefore question if the development of PCRs that are increasingly narrow in scope is the right approach for achieving comparable EPDs, especially when multiple stakeholders are developing PCRs and do not use a classification system to define product categories (Ingwersen and Stevenson 2012).

Summing up, the common goal of PCRs is to harmonize the LCA methodology in a specific product group, but many of the PCRs and core PCRs have been updated in recent years, and existing research on EPD comparability shows that lack of harmonisation is possible both in theory and practice due to several factors and indicates that issue is not easily solved. Yet, the practical implications of this lack of harmonisation remain unclear.

In this context, the analysis here presented aimed to investigate how differences across PCRs affect EPD results, starting from the hypothesis that, for the same identical product, one can in principle produce several formally compliant EPDs with substantially different results. The aim of this study is thus to assess how different rule sets influence the EPD results of the same products. We first conducted a review and detailed document analysis of specific guidelines (standards and rule sets) to identify factors that can potentially lead to different results, and then performed a LCA modelling of one specific product varying these factors to quantify the effects of the lack of harmonisation across rule sets. To the best of our knowledge, this is the first study that proposes this kind of comparative analysis both qualitatively and quantitatively.

2 Methods

2.1 Scope of the analysis

We delimited the scope of the analysis to four programme operators: EPD Denmark, EPD Norway, EPD International and IBU. According to Jørgensen et al. (2021) EPDs representative of the Danish building sector are primarily published by these four organisations. General recognition between the four programme operators is promoted by an umbrella organisation to eliminate barriers to trade (ECO Platform 2022). Details about the recognition agreements between these operators and standards and rule sets developed by each are shown in Fig. 2. Additional information on the four program operators and related mutual recognition agreements are provided in SI1 (Konradsen et al. 2023).

We set to understand how much EPD results can vary due to the differences in general programme instructions (GPIs), Part A PCRs and c-PCRs—as all these guidelines include modelling rules. In general, GPIs state how a EPD programme operator operates and what kind of EPDs it publishes, e.g., if it only focuses on building-related products or accepts EPDs for all types of products but can also include methodological rules. Part A PCRs describe via modelling rules how an EPD programme operator "enforces" or "interprets" the core PCRs. Lastly, c-PCRs support EPD developers when developing an EPD for a specific product by including product-specific modelling rules.

While several EPD types exist, such as sector EPDs, product-specific EPDs or project EPDs, we focused only on product-specific EPDs as they are compliant with the ISO 14025 definition. We then focus on the building sector because EPDs are widely used there and chose the case of a virtual window produced in Denmark.

2.2 Systematic document analysis of differences in guidelines

To assess the level of harmonisation between the four programme operators, we conducted a systematic document analysis (Bowen 2009) and reviewed the content of their

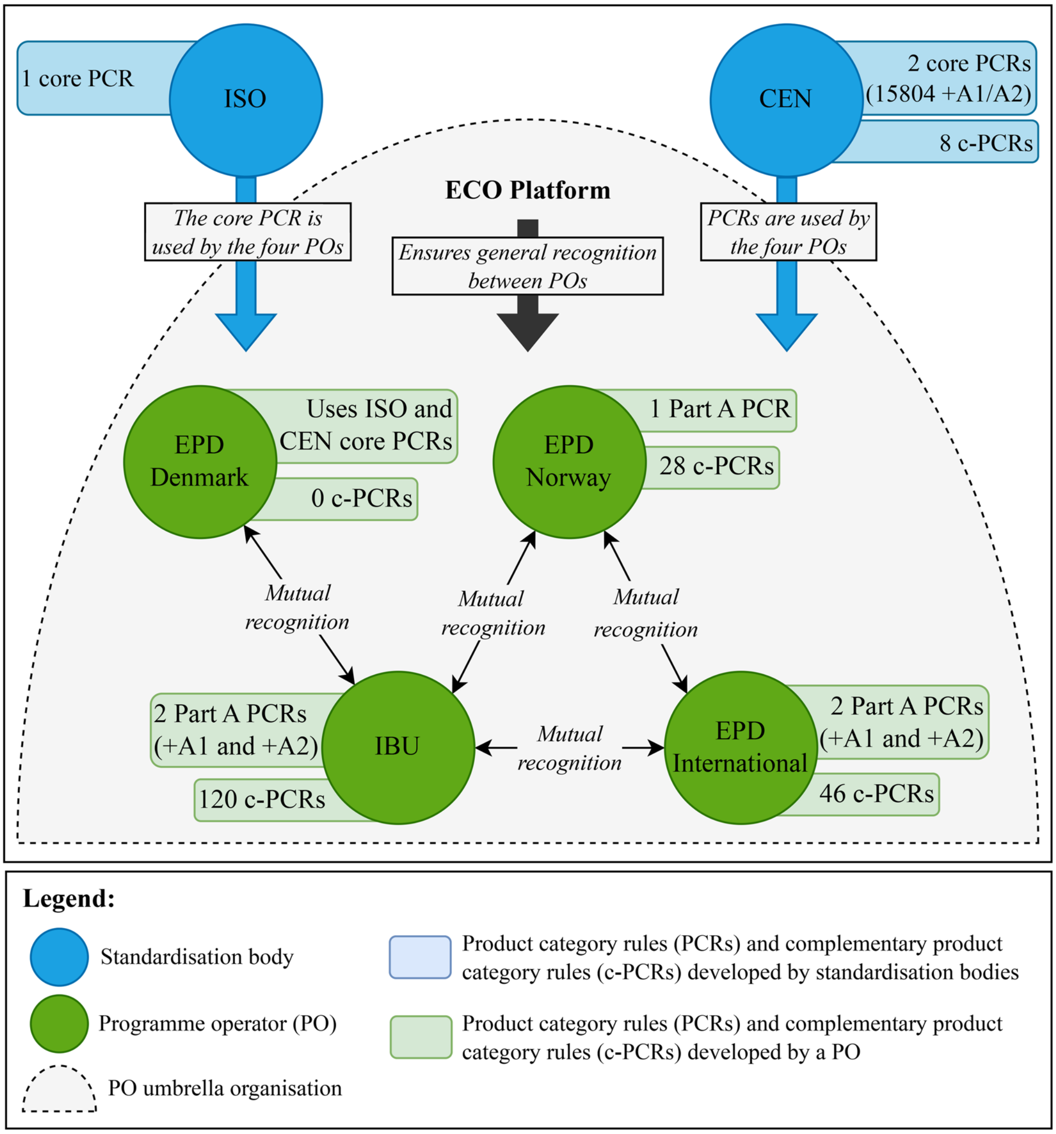

Fig. 2 Standardisation bodies and programme operators relevant for the EPD system in the Danish building sector. The figure also shows the total number of rule sets with construction materials and products developed by each standardisation body or programme operator

GPIs, Part A PCRs and the c-PCRs respectively, for the product group of windows and doors. Details about the standards and rule sets reviewed for this study are provided in SI1 (Konradsen et al. 2023).

The analysis specifically focused on identifying qualitative and quantitative differences from the reviewed documents, which influence EPD results and hence limit the accuracy of EPD comparison. The distinction between qualitative and quantitative differences was also made to select which parameters to include in the LCA modelling. While qualitative differences are important to assess comparability, they cannot be explored via a LCA model.

Specifically, we compared (1) the GPIs of the four programme operators, (2) the Part A PCRs of EPD International, EPD Norway and IBU and (3) the c-PCRs for the product category for windows and doors published by EPD International, EPD Norway, IBU and CEN.[1] The product category for windows and doors was selected on an initial screening of the c-PCRs published by the program operators and CEN. The product category was selected because IBU, EPD Norway, EPD International, and CEN have developed a c-PCR for it and since this product category contains a manageable number of documents compared to, e.g., the product category of concrete.

[1] The c-PCR from CEN was included because EPD Denmark recognises the use of this rule set.

Following the document analysis approach of Bowen (2009), firstly the documents investigated were thoroughly read and interpreted to find and appraise the data in the documents. Secondly, the data were coded and organised into categories. Finally, the data were synthesised and compared.

The following information was retrieved and categorized:

- Governing standards: information on whether and when one ruleset overrule another.
- Goal and scope: requirements about which functional unit or declared unit to be used, which allocation criteria, which system boundary/modules to be included; the geographical scope, assumptions, cut-off criteria and reference service life.
- Life cycle inventory (LCI): requirements regarding data quality and the electricity mix to be used.
- Life cycle impact assessment (LCIA): requirements regarding which impact categories to report, and characterisation factors to use.
- Requirements about interpretation and reporting of results.
- Other requirements such as those regarding validity period, documentation of data and assumptions, which LCI databases and LCA software are allowed to be used.

These categories were selected based on the five steps of EPD development as described by EN 15804+A1 and +A2 (from goal and scope to reporting), a review of previous literature and the approach for comparing PCRs and EPDs described by Gelowitz and McArthur (2017). After the data were coded and organised, we made a comparison within each document group. For example, comparing requirements between two different GPIs, and across document groups, or comparing information from GPIs with information from Part A PCRs, as some of the documents overrule others.

2.3 Life cycle assessment of triple-glazed window

We conducted the LCA for a triple-glazed window measuring 1.23 m × 1.48 m with a wood frame and aluminium cladding that we assumed is produced by a fictive manufacturer located in Denmark. We used the standard size of a window according to EN 14351-1. Windows with a wooden frame and aluminium cladding are commonly used in Denmark, and triple glaze lives up to the energy requirements in the Danish building code. Aluminium cladding gives weather resistance, while wood gives isolating properties.

The modelling follows the EN 15804+A2[2] structure for conducting an EPD from goal and scope to interpretation. Based on the suggestions for functional units in the c-PCRs and the study of Horup et al. (2019), the functional unit was defined as *1 m^2 of window with U value of 0.5 W/m^2 K and a reference service life of 25 years.* The energy requirements for windows were considered by specifying a *U* value: it determines the heat loss through the window; the lower the value, the lower the heat loss. We also assumed that this is maintained throughout the reference service life of the window, hence potential heat loss is not further considered in the LCA. This assumption is derived from and backed by The Norwegian EPD Foundation (2020). The reference service life of the window was also included in the functional unit as it is a key parameter for determining the product's environmental impact. In EN 15804+A2, reference service life is defined *as* "*service life of a construction product which is known to be expected under a set of reference in use conditions*" (CEN 2019). Based on Aaggard et al. (2013), we estimated that windows typically are replaced every 25 years in Denmark. Windows may however have longer lifespans, and some c-PCRs provide default reference service life values if the data on service life is not provided.

Figure 3 shows the product system with material and energy inputs in each life cycle stage. EPDs of buildings use a more specific classification of life cycle stages compared to ISO: product stage (A1-A3), construction stage (A4-A5), end-of-life stage (C1-C4) and benefits and loads beyond system boundary (D), were modelled here. With respect to the use stage, only maintenance stage (B2) was considered to have inputs. Other use stages (B1 and B3-B7) do not include any inputs, because we assumed no replacement or refurbishment during the lifetime and because the operational energy (module B6) and operational water consumption (module B7) can only be calculated at building level. It is therefore only the use of water and detergent for window washing in module B2 that is included as an input in the use stage. The full life cycle inventory is provided in Supporting information SI2 (Konradsen et al. 2023). The last stage of reporting (cf. clauses 7 and 8) in EN 15804+A2 was excluded as not relevant for this research. The foreground data for the window was obtained from a Norwegian EPD on triple-glazed window (The Norwegian EPD Foundation 2020) and Salazar and Sowlati (2008), which was linked to the background data from Ecoinvent v3.8 (2023).

2.4 Scenarios compared in the study

A window manufacturer might or might not be aware that EPD results may vary depending on whether the EPD is published through one or another programme operator. The

[2] The + A1 standard expired in November 2022, and the + A2 standard was developed in 2019 with the purpose of replacing the + A1 standard. There was a 3-year transition period, which is why both + A1 and + A2 were included in the research. Currently, all EPDs in Denmark are developed in accordance with + A2, while results are calculated in accordance with both standards. The EPD presents the + A2 results, and an appendix with the EPD presents the + A1 results.

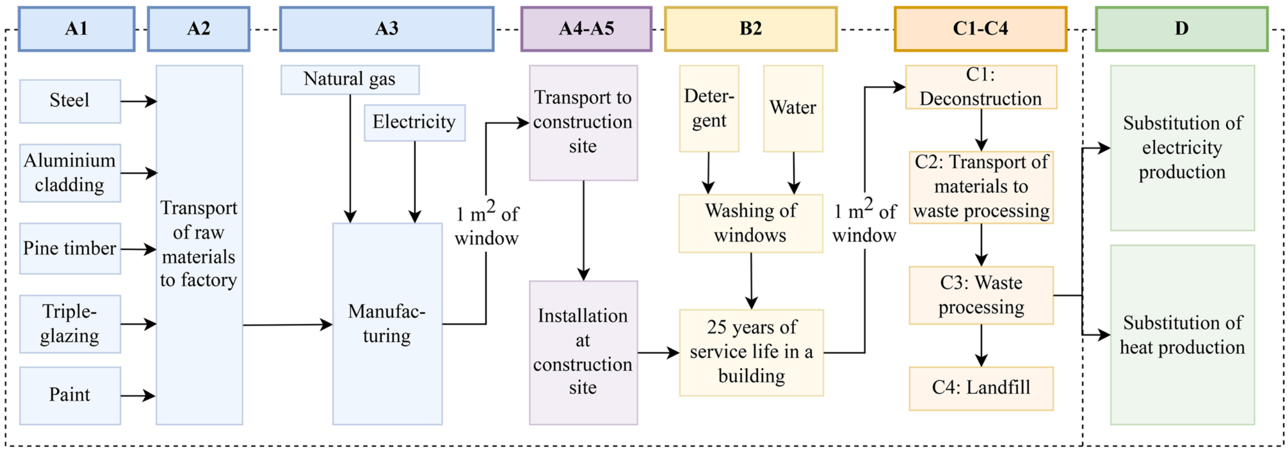

Fig. 3 Product system for the triple-glazed window with wood frame and aluminium cladding

impact that the quantitative differences identified via the document analysis can have on EPD results was tested by developing a total of ten LCA scenarios for the same triple-glazed window. To be more specific, what we identify with the generic term "scenarios" represent different possible and equally compliant choices for LCA models behind the window's EPD. The selection of scenarios is based on the results of the document analysis (cf. Sections 3.1 and 3.2) as the scenarios mirror the major quantitative differences identified in this analysis. These differences regard the modelling of service life, end-of-life, transport in A4, washing, the modelling approach (attributional or consequential) and the inclusion of capital goods. The supporting information reports the full life cycle inventory corresponding to each scenario (SI2) (Konradsen et al. 2023).

All four programme operators allow the use of "green" energy certificates in EPD development. This means that a manufacturer can improve the environmental performance of its product by buying certificates on renewable electricity, and thereby model the EPD with such green electricity instead of a residual energy mix (EPD Denmark, EPD International) or the national grid mix (EPD Norway, IBU). We assumed that the electricity mix based on the green certificates is a mix with 100% renewable power from wind turbines. All scenarios named "-e" use a green electricity mix, and those named "-r" and "-b" use the residual energy mix and the national grid mix respectively. The EPD rule sets used for the base scenario (REF-r) are based on EPD Denmark,[3] as the general programme instructions of this programme operator allows publication of EPDs developed in accordance with one core PCR. Hence, the most recent core PCR EN15804+A2 was used. A second reference scenario (REF-e) was included that assumes a green electricity mix if the manufacturer buys green energy certificates.

Two other scenarios for EPD Denmark (DEN-r, DEN-e) where additional rules from the CEN c-PCR for windows and doors are applied. Two scenarios for IBU (IBU-b, IBU-e) were developed using IBU specific Part A PCR for building products and a c-PCR for windows and doors. As shown by the results of the document analysis, a different reference service life can be used depending on which c-PCR the EPD is developed in accordance with. In the DEN scenarios, this is set to 30 years, while 50 years is the assumption used in the IBU scenarios. The reference flow for these scenarios changes accordingly: 0.83 m^2 of window and 0.5 m^2 of window respectively (in other words: a window with a 25-year lifetime can fulfil the functional unit 1.2 times in the DEN scenarios and two times in the IBU scenarios respectively). The inventory for module B2 (use stage) does not change between these scenarios since use and therefore maintenance are still assumed for 25 years. The two scenarios for EPD Norway (NOR-b, NOR-e) include requirements in from the Norwegian Part A PCR for construction goods and services and c-PCR for windows and doors. These provide specific rules to model module B2 and capital goods (personnel activities are not included due to lack of data).

The two scenarios developed for EPD International (INT-r, INT-e) were developed based on the two different inventory modelling approaches. The EPD International (INT-r) scenario was developed using the attributional approach based on its Part A PCR and c-PCR for windows and doors. This is the most common within the EPD system. However, EPD International's general programme instructions allow conducting a consequential LCA when module D is included in

[3] EPD Denmark has not published a Part A PCR or c-PCR like the other programme operators.

Table 1 LCA modelling choices in each scenario

Scenario	Rule sets used	Energy mix in A3	Service life (years)	End-of-life	Transport in A4 (km)	Washing (p/year)	Approach	Capital goods
REF-r	EN15804 A2	Danish residual mix	25	Incineration	280	4	Attributional	No
REF-e	EN15804 A2	Green certificates	25	Incineration	280	4	Attributional	No
DEN-r	EN15804 A2; c-PCR EN 17213:2020	Danish residual mix	30	Recycling	400	4	Attributional	No
DEN-e	EN15804 A2; c-PCR EN 17213:2020	Green certificates	30	Recycling	400	4	Attributional	No
IBU-b	PCR for building products Part A (EN 15804+A2), v 1.2 Part B: Requirements on the EPD for Windows and doors, v 1.5	Danish national grid mix	50	Incineration	280	4	Attributional	No
IBU-e	PCR for building products Part A (EN 15804+A2), v 1.2 Part B: Requirements on the EPD for Windows and doors, version 1.5	Green certificates	50	Incineration	280	4	Attributional	No
NOR-b	NPCR Part A: Construction products and services, v2.0 NPCR 014:2019: Part B for windows and doors v1	Danish national grid mix	25	Incineration	300	3	Attributional	Yes
NOR-e	NPCR Part A: Construction products and services, v2.0 NPCR 014:2019: Part B for windows and doors v1	Green certificates	25	Incineration	300	3	Attributional	Yes
INT-r	PCR 2019:14: Construction products, version 1.11 c-PCR-007 (to PCR 2019:14) Windows and doors (EN 17213:2020)	Danish residual mix	25	Incineration	280	4	Attributional	No
INT-e	General programme instructions for the International EPD System, v 4.0	Green certificates	25	Incineration	280	4	Consequential	No

LCA. In addition, this approach could be adopted only for the green electricity scenario as the choice of source electricity is allowed if there is documentation (green certificates) on it. Table 1 gives an overview of all scenarios.

In all scenarios, we used the LCIA method for EN 15804+A2 in the software SimaPro—which is a realistic set up for a EPD developer. The method calculates 19 environmental impact categories, yet we only included the 13 ones that are mandatory to report (CEN 2019).

3 Results

3.1 Results of document review—qualitative differences

One of the differences relevant to highlight is which product-specific construction EPDs the programme operators can publish. EPD Denmark, EPD Norway and EPD International publish *product-specific EPDs* as described in their GPIs.

This product-specific EPD is either declared for a single manufacturing site, multiple manufacturing sites (based on the average), multiple similar products from one manufacturing site (based on the average) or multiple similar products from multiple manufacturing sites (based on the average) (EPD Norway 2019; EPD Denmark 2020; EPD International 2021). In addition, IBU publishes a *representative product-specific EPD*, which is an EPD of a single product that is deemed representative for a selected group of similar products, and a *model product-specific EPD*, which is an EPD that declares the worst-case scenario for a selected group of products (IBU 2021c). The definition of a *product-specific EPD* is thus not univocal. Even under the same definition, the input data can vary depending on whether data is collected throughout many manufacturing sites (e.g., located in various places in Europe) versus a single manufacturing site, or whether data are averaged across different products deemed similar. If decision-makers unaware of these distinctions compare different product-specific EPD types with each other, this can result in flawed conclusions.

3.1.1 Differences in functional and declared units

One of the main differences between guidelines is the application of different functional units and declared units. Declared units are often used within the EPD system even though this concept is not present in the ISO 14040-44 standards. The standards specify that LCA is exclusively structured around a functional unit that quantifies the function of the studied product system (ISO 2008a, b). A declared unit quantifies instead the amount of product under analysis (CEN 2013, 2019; ISO 2017). The application of a declared rather than functional unit is allowed in several instances in accordance with the three core PCRs, e.g., when a product has multiple functions (CEN 2013, 2019) or when the function of the product at the building level is unknown (ISO 2017). Based on these statements, we find that it is almost always possible to apply a declared instead of functional unit—unless a c-PCR specifically specifies a functional unit which shall be applied. While declared units are specified in all c-PCRs, only EPD Norway specifies functional units for doors and windows. Only CEN and EPD International use the same declared unit for the product category of windows and doors: "*1 m^2 of window or door respectively*" without specifying any function related to the product. Whilst some declared units are too specific, e.g., "*1 produced window measuring 1.23 m × 1.48 m (reference size from EN 14351-1) with an essential parameter (u-value, fire classification, noise reduction) and waste treatment at end-of-life*". A functional unit must be developed to have a common point of reference for comparative LCAs as the lack of equal functions may lead to unreasonable comparisons (Weidema et al. 2004; Furberg et al. 2022). The programme operators and CEN use different versions of both declared units and functional units; this can make EPDs for both windows and doors incomparable. There is no consensus between the programme operators for how to quantify the function of windows and doors nor the amount of product despite having rule sets for specific for this product category.

3.1.2 Differences in approaches for co-product allocation

Common for all programme operators is their first rule on allocation: it must be avoided if possible and justified if it cannot be avoided (EPD Norway 2019; EPD Denmark 2020; EPD International 2021; IBU 2021a). Furthermore, all programme operators agree on the allocation principle (cf. ISO 14040 and ISO 14044), where mass allocation is prioritised, and economic allocation is accepted if the other options are not possible. However, both EPD International and EPD Denmark refer to EN 15804+A2 in their GPIs for rules on allocation (EPD Denmark 2020; EPD International 2021), whereas EPD Norway refers to ISO 14044 in their GPI and in their Part A PCR, wherein additional rules can be specified (EPD Norway 2019, 2021). However, EPD Norway further states in their c-PCR for windows and doors that allocation must follow the rules presented in EN 15804+A2. Furthermore, co-product allocation is approached differently in EN 15804 (both +A1 and A2) and ISO 21930 which affects Part A PCRs since they aim to implement all three core PCRs (EN 15804+A1, EN 15804+A2 and ISO 21930). To solve this issue, EPD Norway has made additional specifications which align with all core PCRs (EPD Norway 2021), while EPD International states that the co-product allocation in ISO 21930 is not credible to use due to possible double counting and refers to the allocation rules in their Part A PCR which tries to avoid double counting (EPD International 2021). While IBU's Part A PCR states that waste leaving module A1-A3 should be considered as a co-product, and therefore the benefits must not be assigned to module D, this contradicts EN 15804+A2, where "as a general rule, potential loads or benefits from A1-A3 do not appear in module D" (CEN 2019).

3.1.3 Differences in the use of specific background databases

Using product-specific data is the highest priority in EPD development for EPD Denmark, EPD International and IBU. In contrast, EPD Norway prioritises data from EPDs over product-specific data. This is problematic, as EPD Norway allows EPDs to be developed based on inputs which may be affected by the harmonisation issues. Moreover, the GPI of EPD Norway specifies that data from ecoinvent should be used to model national electricity production, while IBU allows the use of three databases: Ökobaudat, ecoinvent and

GaBi. IBU states that "as *a rule, consistent background data shall be used*" (IBU 2021a, b); however, there are contradictions to this rule based on IBU's suggestions on the use of background databases. IBU suggests using the GaBi database for companies registered in Germany, when it comes to energy, transport and auxiliary background activities. IBU additionally allows using the Ökobaudat database for data on ancillary materials produced in Germany, in case no other data is available. Finally, IBU leaves the possibility to use ecoinvent. However, IBU acknowledges that "the *comparability of EPD calculated with different databases is limited*" (IBU 2021a, b). Therefore, different databases can be used in different EPDs, and even multiple databases in the same EPD which creates serious consistency problems, with evident issues of comparability.

3.2 Results of document review—quantitative differences

3.2.1 Using both attributional and consequential approaches

There are two main modelling approaches to conduct LCA: attributional and consequential. ISO 14040–44 allows both, but attributional LCA is the most common approach used within the EPD system. One may argue that in principle both approaches are allowed within the EPD system, since ISO 14025 uses ISO 14040–44 as normative references. EPD International states in its GPI, "*the LCA modelling approach of the International EPD System is attributional LCA*" (EPD International 2021). Yet, it is also stated in EPD International's GPI that if a PCR allows "*the declaration of life-cycle stages or modules based on consequential LCA modelling, such as module D of EN 15804, the results of those life-cycle stages/modules shall always be separately declared*" (EPD International 2021). This formulation is obscure, but we interpreted it as EN 15804 (both editions) allowing consequential LCA modelling if it is declared separately in the EPD, thus making both attributional and consequential modelling formally applicable for EPD development. We conclude therefore that since the EPD system allows both approaches, a comparison between attributional and consequential EPDs can therefore happen in practice. One may however argue that it makes little sense to compare attributional and consequential LCA results, since the two approaches are fundamentally different and answer different questions (Weidema et al. 2018; EPD Denmark 2020), leading again to a comparability problem.

3.2.2 Using green energy certificates in LCA modelling

All programme operators recognise the use of green certificates. However, if a manufacturer does not use green energy certificates, the choice of electricity use differs depending on the programme operators. For EPD Denmark and EPD International, the electricity should come from the residual mix, whilst for EPD Norway and IBU, the electricity should come from the national grid mix Residual mix is the electricity mix without the electricity tracked through green certificates (Ecoinvent v3.8 2023). EPD Norway specifies that losses when transforming to different levels of voltage must be included in the calculation. Whilst the other programme operators do not state anything regarding losses. Differences in rule sets with respect to electricity use can potentially lead to variability in the results as electricity use often has a substantial influence on a product's environmental impact.

3.2.3 Inclusion of capital goods and personnel

EPD Norway is the only programme operator that includes capital goods and personnel activities in their EPD development, stating that these inputs must be included unless they can be justified to be under the cut-off criteria of 1%. However, EPD International specifically states that these activities are not to be included within the system boundary. This indicates an inconsistency in system boundary definition between EPDs published by EPD Norway and EPD International reducing the comparability between these EPDs.

3.2.4 Variations in the length of the reference service life

The reference service life is only mandatory to declare in an EPD, if module B is included or if it is a cradle-to-grave EPDs. Part A PCRs and c-PCRs deviate in how the reference service life is specified for windows and doors.

All the selected c-PCRs except the CEN c-PCR state that the reference service life depends on the product and the individual manufacturer. Nevertheless, IBU includes a default reference service life of 50 years for a window if the manufacturer cannot determine the reference service life themselves. Similarly, the CEN c-PCR states that for windows, a reference service life of up to 30 years can be used in case documentation on the real service life is missing.

3.2.5 Variations in water usage for cleaning in module B2

The document analysis of the c-PCRs shows that EPD Norway explicitly describes what is expected to be included for the water usage during windows maintenance: the water usage is determined to cover window washing three times per year and the manufacturer is responsible for providing guidance procedures. However, EN 15804 (both editions) and the other programme operators' documents do not specify how windows maintenance should be modelled, therefore leading to a difference in module B2 between EPDs published by the Norwegian programme operator and the others.

3.2.6 Different recycling percentages for end-of-life

Programme operators follow the rules and guidance from the core PCRs meaning that end-of-life scenarios shall be realistic, representative and include one or more likely alternatives (CEN 2013, 2019) (ISO 2017). IBU explicitly requires EPDs to include 100% scenarios for all waste management alternatives.[4] This makes it possible for the EPD user to adjust the results based on the specific settings of the building LCA. For example, if the EPD user knows that Denmark has a 60% recycling rate and 40% incineration rate, they can combine the waste treatment alternatives to fit the Danish context (Anderson et al. 2019). Instead, the CEN c-PCR for windows and doors recommends using "*a conservative recycling efficiency of 90% for all types of secondary materials entering module D*" (CEN 2020). The CEN c-PCR also provides default end-of-life scenarios for metal, PVC-U and timber windows and doors sets, which can be used in the absence of data, stating that the scenarios are "*designed to establish a credible but conservative picture of a product's end-of-life treatment based on current end-of-life practices taking place in Europe*" (CEN 2020). However, we were unable to find any data from the Danish waste management industry that support the assumptions in these default scenarios. We thus conclude that the different approaches for end-of-life scenarios can lead to comparability problems.

3.2.7 Different default values of transport distances in module A4

Programme operators indicate different default distances to be used in module A4 (transport to construction site). IBU and EPD International do not provide default transport values in their guidelines. The measurable differences can be found in the c-PCRs, where EPD Norway has additional requirements for module A4: the default value is determined to be 300 km and truck is selected as the default vehicle. However, the CEN c-PCR has determined a default distance of 400 km and does not specify a type of default vehicle. We find thus direct evidence of lack of harmonisation and contradictory rules regarding what to include in module A4.

3.3 Results of LCA modelling

Figures 4 and 5 show the results for the environmental impact category Climate Change in kg CO2-eq from each life cycle stage considered in this study for all scenarios with national grid mix and green electricity mix respectively. Results for A1-A3 have been aggregated as allowed by EN 15804+A2 (CEN 2019) and as typically done in EPDs (EPD Denmark and BUILD 2021). It also shows the total impact from modules A1-C4. In the following, the tendencies described above are presented only using the results for the environmental impact category climate change. We define a *significant* difference in the results to be ± 10%, since this rule is used within the EPD system when assessing whether an EPD's results should be updated (CEN 2019).

The results for EPD Denmark using CEN c-PCR (DEN-r and DEN-e) vary more than ± 10% from the base scenarios (REF-r and REF-e) in 10 out of 13 environmental impact categories. The difference between REF-r and DEN-r is due to the choice of reference service life[5] and leading to a difference of – 17% from the base scenario. Moreover, there is substantial difference when comparing the module D in these two scenarios, as the increased recycling of materials considered in DEN-r. This is due to the relatively low benefits for base scenarios REF-r and REF-e (– 6 and – 7 kg CO_2-eq respectively), compared to the benefits for DEN-r and DEN-e (– 34 and – 35 kg CO_2-eq respectively).

The results for IBU (IBU-b and IBU-e) also vary more than ± 10% from the base scenarios in all environmental impact categories. The deviation in results for IBU-b is due to the applied reference service life of 50 years instead of 25 years that explains why IBU-b values are 50% lower than REF-r values and shows how the choice of reference service life is of great significance. Yet, the overall percentage difference between IBU-b and REF-r is – 43%, since the impact in maintenance module B2 is the same.

The difference in the total results from EPD International (INT-r) and EPD Norway (NOR-b) as compared to the base scenario (REF-r) is not significant in scenarios modelled with national and residual grid mix respectively. The scenario for INT-r is the scenario most aligned with base scenario (REF-r). The results from NOR-b for the production phase (A1-A3) and maintenance (B2) are significantly different (– 12% and + 83% respectively) as compared to the same modules in REF-r. However, this evens out in the total result (A1-C4). It is worth noting that the inclusion of capital goods in the requirements of EPD Norway has no substantial impact on the aggregated result for A1-A3.

[4] If in Denmark 40% of windows are recycled, and the remaining 60% is incinerated, an EPD should show the environmental impact of 100% recycling and 100% incineration and then it is also allowed to show the impact for the 40/60 mix.

[5] DK-1: 25 years/30 years × 100 = 83% of the product is needed to provide the FU.

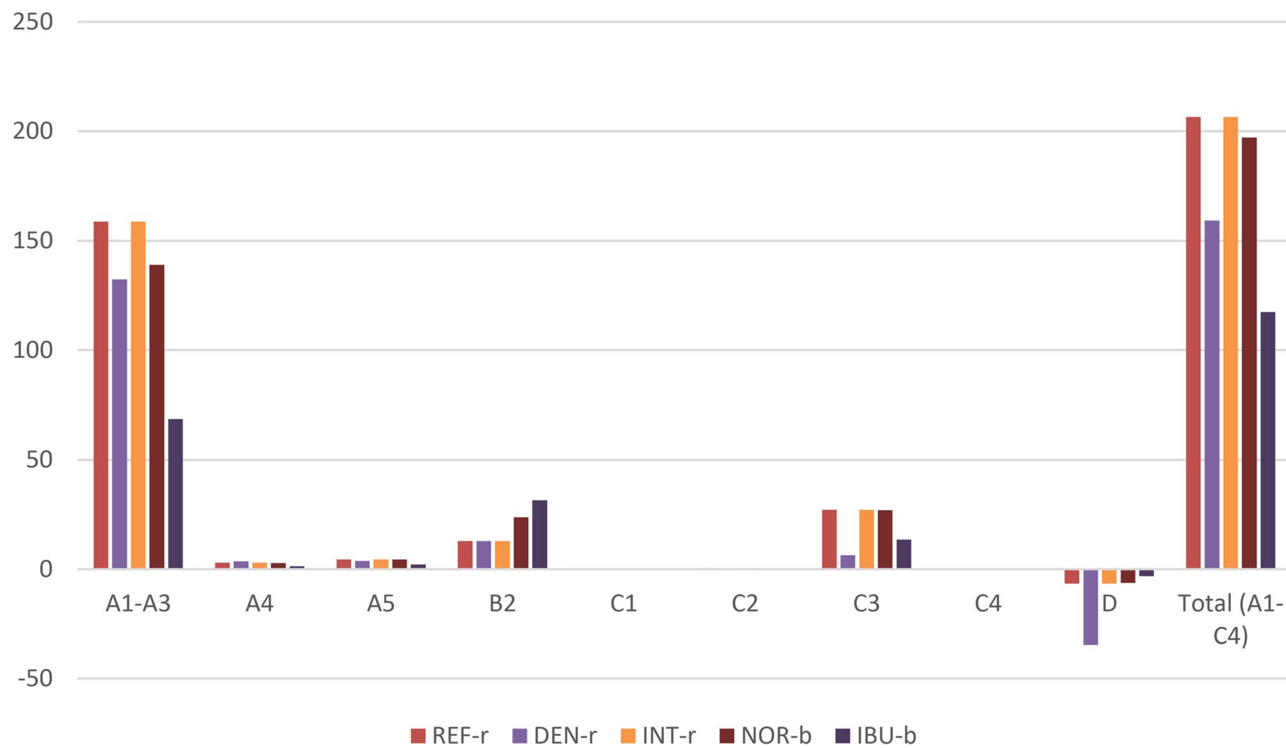

Fig. 4 Global warming impact for all scenarios with the residual or national grid mix

The influence of the use of green energy certificates reduces the overall results for all scenarios as expected. However, the general trend in the results remains the same. There are no substantial noticeable differences in results from EPD Norway (NOR-e) and EPD International (INT-e) for the production phase (A1-A3) when compared to the base scenario (REF-e). However, this is not reflected in the overall results due to the negative contribution of module D. The differences in the results for NOR-e is related to modelling differences in modules A4 (transport to site) and B2 (maintenance). The difference in results for INT-e can be derived from the use of the consequential database, showing that the choice of system model and database has a major influence on the results (see SI3 for more details). If INT-e was developed using the attributional modelling approach, the results would overlap with scenario REF-e as seen previously for the results of scenarios REF-r and INT-r.

We observe the same tendency across most of the 13 environmental impact categories. A detailed analysis of the most significant differences for other categories other than climate change, that deviate from the results above, is provided in SI3 (Konradsen et al. 2023).

4 Discussion

4.1 On harmonisation of life cycle assessment results

Lack of harmonisation has been an issue within the EPD system since the 2000s (Bogeskär et al. 2002), and one may question whether it is possible to develop a standardised approach for LCA using such a decentralized management process, with

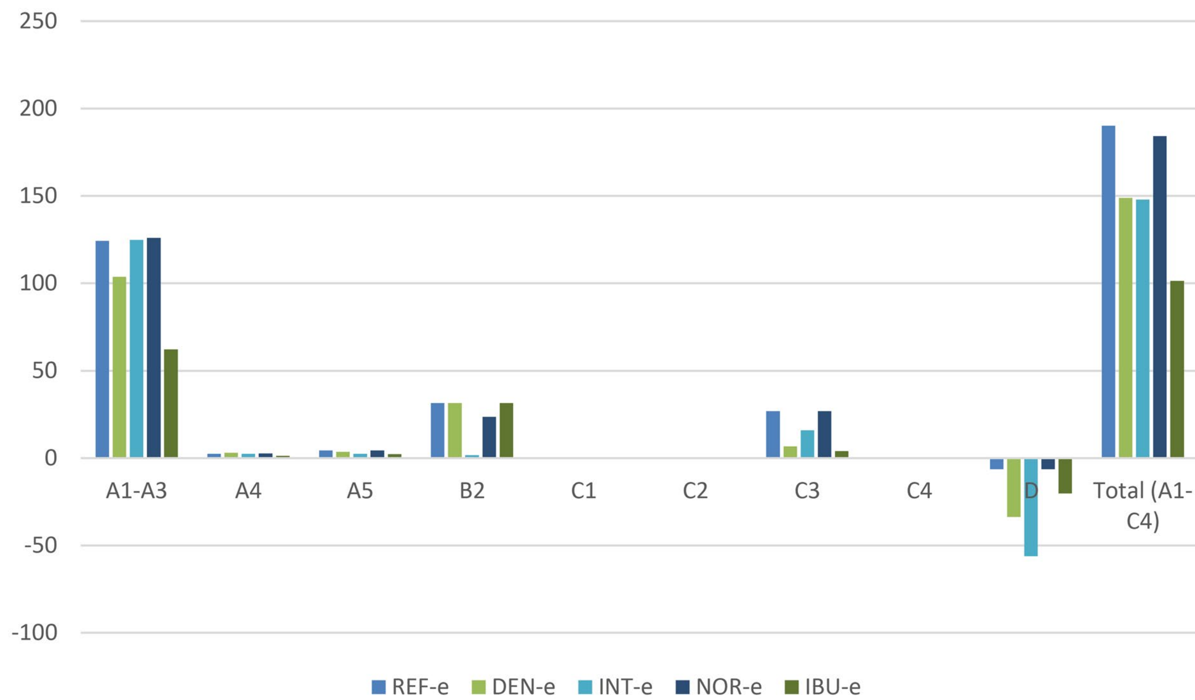

Fig. 5 Global warming impact for all scenarios with green certificate mix

different operators developing their own rules and guidelines at country level and different stakeholders developing subsets of these rules and guidelines at product level.

According to stakeholders in the EPD system interviewed during the initial phases of this research (Hansen and Jeppesen 2022) that despite the general belief that the harmonisation of LCA practice is a desirable objective, there is a disagreement on how to achieve it. Some are of the opinion that it will take too long to harmonize LCA with the current process. Instead, others think that the harmonisation process should start over in a different shape, for example, with the European Commission in the role of overall European programme operator. This could be a solution to harmonisation issues, since it would entail that only the Commission should be able to develop the necessary product category rules (Hirsbak 2022). The European Commission has tried to do this through the development of EN 15804+A2 (EPD Denmark 2021; International 2021; Norway 2021). EPDs following EN 15804+A2 apply the impact categories from the PEF system (EPD Denmark 2021; EPD International 2021; EPD Norway 2021), yet the two systems are not comparable due to methodological differences, such as cut-off rules, modelling approach and allocation rules (Del Borghi et al. 2020). Hence, it is questionable whether the centralisation of the guideline-drafting process can be a solution as the EPD system is challenged by sectorial interests.

More in general, the EPD system is the symptom of a more general tendency that we could label as the "consumerism" of LCA. By this term, we intend the proliferation of LCA models, not necessarily due to a real need for product improvement but rather due to a desire to communicate product and gain market advantage by declaring better environmental performance compared to competitors or alternative products in the market. Given these premises, the natural consequence of LCA consumerism has been a proliferation of guidelines as well as of "one-click" tools where the process of LCA model building has either been regulated to an extreme level of detail via consensus-building initiatives, or bypassed entirely in favour of black-box calculators able to provide results fast but without providing context nor requiring specific skills or understanding of the underlying data and modelling choices. These trends might have contributed to create the unreasonable expectation that LCA models built by different people in different contexts should lead to an identical numerical outcome. Excessive focus on the numerical outcome and on compliance with a chosen set of rules is used to justify the outcome. We observe as a side barrier to harmonisation also the lack of transparency in the documentation of LCA results and underlying models in the EPD system, which is also paradoxical as it appears that producers are as eager to show good environmental performance as reluctant to disclose the data. The original meaning of LCA—reflection and internal process analysis and improvement—seems to have slowly been set aside in favour of a focus on compliance, fast generation of numerical results and external communication to gain competitive advantage. In this context, it is understandable why so much focus is put on developing guidelines for product-specific environmental declarations. In this study, we show that these are not harmonised—because the same product can obtain significantly different scores depending on the choice of guideline—this is particularly problematic and demonstrates that the system is not working as expected to ensure comparability.

4.2 Comparison with previous studies

As presented by AzariJafari et al. (2021) and Ingwersen and Stevenson (2012), the selection of LCI databases further impacts the LCA results, where it is deduced that IBU has an interest in using the GaBi and Okobau databases. It would be relevant to include data from Okobau and GaBi in the analysis to determine how much the EPD results can vary due to different databases. Differences of up to 20% in specific impact indicator result have been previously reported when using different databases in the analysis (Stiller 2022).

This study confirmed previous results by AzariJafari et al. (2021) and Subramanian et al. (2012), since one of the main causes for lack of harmonisation derives from c-PCRs being published by different programme operators. We find that overlapping PCRs are still a critical cause of harmonisation issues, which Gelowitz and McArthur (2017) and Subramanian et al. (2012) also demonstrated. We also confirm that the excessive room for interpretation is still an issue in EPD-related standards, as highlighted in previous studies (Minkov et al. 2015; Achenbach et al. 2016; Anderson et al. 2019). We also confirm that different guidelines prescribe the use of different LCI databases and allocation rules (Ingwersen and Stevenson 2012; Lauri et al. 2020).

According to several previous studies (Subramanian et al. 2012; Hunsager et al. 2014; Minkov et al. 2015; Toniolo et al. 2019), language barriers can hinder harmonisation, for example, when different European programme operators act in their local language. However, this was not among the limitations of this research because all selected programme operators use English in the guidelines.

4.3 Limitations of the analysis

It is a complex task to navigate the rules for EPD development when the programme operators implement the CEN c-PCR differently. It was beyond the scope of this research to test the variations in EPD development for all core PCRs, GPIs, Part A PCRs and c-PCRs. The analysis was therefore limited to EPD developed based on EN 15804+A2, considered that EN 15804+A1 is only valid until November 2022 and ISO 21930 is primarily used outside of Europe. Limiting the study to EPDs based only on EN 15804+A2 might overlook specific issues. For example, there could be inconsistencies related to the handling of biogenic carbon. Only EN 15804+A2 specifies that biogenic carbon should be accounted for in both module A and module C (i.e. any carbon uptake arising in module A should be balanced out in module C). However, if only module A1-A3 is included in the EPD, then biogenic carbon should not be included. No inconsistency for accounting of biogenic carbon has been found between the 4 programme operators in this study. However, such inconsistencies could be found in EPDs published by other programme operators if they still follow EN 15804+A1.

The idea for this study was to imitate a product-specific, cradle-to-grave EPD for one product, since this EPD type is accepted by all the identified programme operators within the scope of this study. Since the LCA is conducted for a hypothetical product produced by a fictive manufacturer, however, it does not live up to several of the requirements for data quality and cut-off criteria in EN 15804+A2, because simplifications and assumptions were made due to the lack of product and manufacturer-specific details. We believe however that this has no implications for the results, as the differences observed would remain the same also with more compliant cut-off choices.

A point up for discussion is the general validity of these results as the LCA is conducted in a Danish context, i.e. using country-specific conditions for Danish grid mix (A3) transport (A4) and manufacturing (B2) and the substitution of the Danish electricity and heat generation (D). The study scope is also limited to a small part of the global EPD system: four countries and the construction sector. While we cannot prove that the same lack of harmonisation exists for other sectors and geographies, it is reasonable to think that the more countries involved, and the more complex the sectors, the more the lack of harmonisation would be. After all, if such significant differences can be found by delimiting the scope of the experiment to a set of relatively controlled conditions, introducing more variability would likely make comparability worse. One might also argue that one case study is enough to prove that the comparability is not reachable in the EPD system, at least not to the high level that is arguably intended as objective of the programme.

Assumptions in the modelling of the window were made as realistic as possible based on information from published and grey literature, although they were not based on information from a specific manufacturer. The LCA was conducted based on a fictive window in order to prove a point, but one might wonder if such LCA could be approved by a designated third-party verifier. Verifying the LCA with external review would improve the validity of the results, as the assumptions and the interpretation of the standards would be put under closer scrutiny. We also highlight that the LCA is not conducted strictly after EN 15804+A2, where certain aspects are left out due to time-efficiency: e.g., the data collection and quality assessment of the applied data is not examined after Annex E in EN 15804+A2 (CEN 2019).

Another limitation is the lack of multiple product groups included in the document analysis and the LCA, as this research cannot generalise conclusions based on one product case only (windows). Therefore, it would be beneficial to include other product categories in further research, for example, in concrete and wood products, there are at least 21 product categories to further be investigated.

5 Conclusions and recommendations

The study compared different EPD guidelines both qualitatively and quantitatively by developing different models for the same product following different but formally valid methodological choices within the EPD system. Results show that the EPD of a specific product can return very different impact scores if one or the other guideline is followed. In other words, multiple different but at the same time compliant EPDs can be obtained for the same product, highlighting a serious harmonisation issue within the EPD system.

These results indicate that EPDs are not comparable, but more importantly, the EPD system allows several different modelling choices which impact the EPD results significantly. In the worst case, manufacturers can—if they are aware of the harmonisation issues—exploit the methodological differences to their advantage. This means that, in a pessimistic but still possible scenario, manufacturers can deliberately choose to publish their EPDs through the programme operators where the LCA modelling choices favour their products and display the products' best possible environmental performance.

Moreover, the analysis can conclude that using EPDs as input data for building LCAs comes with uncertainties because EPD results depended on the rules of the publishing programme operators. The fundamental role that is intended for EPDs in decarbonisation of the building sector can therefore be questioned.

Exploiting the EPD system's flaws will weaken the credibility of EPDs and undermine the foundation on which decisions on climate and environmental performance are made within the construction industry, e.g., when a building owner decides to buy one material over another based on EPD results.

We conclude by providing a list of recommendations for improved alignment of EPD results. Limit the number of c-PCRs: this study reveals that calculation procedures in the c-PCR vary depending on the programme operator. Therefore, we recommend developing one c-PCR per product group and let this be the only applicable c-PCR included. Align default values: the investigation also showed misalignment between the default values used by the identified programme operators. Learn from verification: use the verification process as feedback to support the revision of guidelines. The programme operators and/or its verifiers once a year go through the EPDs published under each PCR to see if things have done differently—they can then learn from the different approaches and clarify as time goes. Use of just one background database: though it might affect competition and each programme operators would chose different default databases and then the incomparability continues. Specify the methods: increase transparency on the assumptions, methods and approaches used in the calculation of results, for example, the allocation method or the database used. This is especially important to ensure consistency if results from existing EPDs are used as input to making new EPDs. One centralized operator: centralize the administrative structure so that there is one programme operator for a large area such as Europe or at least only one operator for each country; it is currently possible to publish an EP in Germany via three active operators.

While overall we recommend for a more meaningful application of LCA, oriented to product improvement and focused more on process than on result, we believe implementing some of these recommendations could improve comparability and harmonisation between results obtained for LCAs performed within the EPD system.

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Declarations

Conflict of interest The authors declare no competing interests.

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