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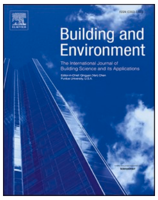

Comparing embodied GHG emissions between environmental product declaration and generic data models: Case of the ZEB laboratory in Trondheim, Norway

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ABSTRACT

The article aims to document and compare the embodied GHG emissions from the construction of the ZEB Laboratory in Trondheim, Norway. The process is of key importance because embodied emissions in Norway constitute the largest part of emissions from the construction sector. Moreover, the recent obligations in building regulations call for early accounting and active reduction of the carbon footprint during the design and execution processes.

The emissions are estimated and compared between two models: firstly, using most data from the Environmental Product Declarations (EPDs), and then, applying only generic data from the ecoinvent database. The main difference derives from the installation of building-integrated photovoltaics (BIPVs), which cover a significant area and show a considerable difference in values. Elsewhere, the general ratio between the generic and EPD products is around 15%. The tendency affects main building materials, such as wood, metal and concrete, while layered products e.g., insulation or covering, show higher emissions in the EPDs.

The assessment and improvement from the early design led to a pioneering building with low embodied emissions compared to other ZEB projects. The generic estimations are obtained quickly and can serve as the starting point to predict and reduce the carbon footprint from the conceptual stage. When a generic database of typical building materials and products is created, it can be used for other projects, shortening the calculation time. The accounting and comparison will be complete when all construction stages specified in the regulations and the building's ambition level are included in the calculations.

1. Introduction

The ZEB Laboratory (Fig. 1) is a four storeys building located at NTNU – Gløshaugen campus in Trondheim, Norway [1]. It has a total heated area of 1742 m^2 and serves as a living office laboratory for SINTEF Community and NTNU Department of Civil and Environmental Engineering. The facility contributes to building knowledge for zero-emission buildings (ZEB), an arena for experimental investigation of user-building interaction, and a laboratory to test new technologies on a large scale [2].

1.1. *Background of GHG accounting*

Declaring or even limiting the emissions of a new building from a life cycle perspective has become mandatory in the Scandinavian countries [3–5]. The introduction of GHG accounting and threshold values in the building regulations set the course towards decreasing the carbon footprint for construction projects from the early design stage [6]. Emissions from building activities are evaluated using reference values or benchmarks in accordance with the methodological choices, background data and tools employed [7]. Following the guidelines, assessments of different residential and non-residential buildings of low-energy buildings and zero-emission buildings in Norway have been performed [8,9].

The article focuses on the greenhouse gas (GHG) emissions of the materials and products used to construct the ZEB Laboratory, encompassed from modules A1–A3 of EN 15978:2011 [10]. An overview of existing benchmark systems in 17 cases from 14 different countries

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Fig. 1. The ZEB laboratory. Photo: Nicola Lolli/SINTEF

concluded that the production stage (A1–A3) is the only stage included in all the systems [7]. Moreover, estimating and compensating for embodied emissions from the building sector in Norway is important because GHG emissions from materials' production and transport constitute the biggest part of emissions of the entire sector [11,12]. In contrast, the leading source of GHG emissions from buildings in Europe is during the operation phase, for instance, using fossil fuels for heating [12,13].

1.2. *Specific vs generic data*

The embodied GHG emissions are accurately estimated when the design process is complete, and a well-defined list of materials and products is available [14]. In such calculations, available environmental product declarations (EPDs) [15] are commonly used for the chosen products. However, a rough estimation is already needed during the conceptual design to assess the highest contributors and make environmental improvements in an interactive decision-making process. For early predesign estimations, when most of the products are yet not defined, various generic datasets (lists) [16] can be utilised and corrected to the actual needs [17]. In the early stages, products are generally defined by material types rather than specific elements, allowing for a wide range of possibilities [18]. The broad span of selection is followed by high uncertainty and variability during the design [19]. Besides, the material quantities for early-stage assessments are not fully accurate [20], and are primarily collected from Building Information Modelling (BIM) model objects [21].

Therefore, exploiting the ratio and uncertainty of the GHG emissions between specific EPDs and generic material emissions at diverse building elements and at the building level would result in faster estimations and early-stage improvements during the iterative design process. An overview of the published peer-reviewed articles that compare the Life Cycle Assessment (LCA) results between EPDs and generic data shows that only a few articles address such differences, and their focus is limited to specific building products. Comparing generic and product-specific LCA databases for a functional unit of 1 kg has been largely carried out by Lasvaux et al. [22]. The results cover different impact assessment categories between the EPDs and ecoinvent generic database for 28 typical building materials and products, and highlight the systematic difference between EPDs and generic data for the same material category. Through the comparison, guidelines for selecting appropriate national generic datasets based on EPDs have been proposed [23]. Most research studies focus on the emission intensity differences between EPDs and generic databases on a product or material level, such as steel products [24], structural wood [25], timber doors [26], wall elements [27], waterproofing solutions [28], hemp fibre [29], or on the challenge of comparability between EPDs [30]. From the state-of-the-art review, none of the articles found in the literature compares the GHG emissions at a building scale between EPD-specific and generic data. This article extends the comparison at a building level and aims to facilitate the emission estimation of new constructions based on generic data depending on the context. The ratios between the two models and between different building elements and materials would be beneficiary for quick estimations and improvements during the design and construction of new buildings. The creation of a comprehensive generic database can be further used to simplify the LCA of new construction projects and contribute to reducing the environmental impact in the construction industry.

1.3. *Objectives*

The article aims to document and compare the life cycle GHG emissions of the materials and products used in the ZEB Laboratory from a cradle-to-gate perspective. The comparison is made between the values obtained from the in-house methodology for calculating GHG emissions developed by the Norwegian ZEB research centre in the form of an Excel-based tool (ZEB tool v.1) [31] versus the generic life cycle inventory data from the ecoinvent database [32]. The calculations are limited to the product stage (modules A1–A3 of EN 15978:2011) and have the objective of answering the following research questions.

- How well does a carbon footprint model based on generic data correspond with a specific building calculated with specific data?
- Are there systematic differences between the carbon footprint based on specific versus generic data? If so, how can such differences guide the data collection regarding the need for specific data for materials or product categories?
- Is there a correlation between the uncertainty level in the generic data and the magnitude of difference between generic vs specific data?
- What is the correlation between the Global Warming Potential (GWP) and other impact categories?

Furthermore, the carbon footprint of an advanced zero-emission building with novel solutions is presented, and the results are broken down according to both building element and material levels. The assessment and improvement processes since the sketch-up design resulted in an innovative building with low embodied emissions compared to other ZEB projects in Norway, despite the building's complexity.

2. Materials and method

2.1. The ZEB laboratory

2.1.1. General description

The scope of the ZEB Laboratory is to develop, explore, test, and demonstrate innovative components and solutions in mutual interaction with the building occupants. The building comprises a four-story living laboratory with a total floor area of 1742 square meters (BRA). It is located in Trondheim (Norway), on the NTNU – Gløshaugen campus, near the existing facilities of SINTEF Community and NTNU Department of Civil and Environmental Engineering. The design process started in 2016, and construction began in May 2019. The laboratory was inaugurated and became ready for test operation in March 2020.

Building development was a collaborative and novel effort between a leading contractor, consultants and subcontractors. NTNU and SINTEF experts, in collaboration with external architects, designers and contractors, were involved in all stages of the development. In an innovative approach, the building's ambitions were continuously improved by selecting the solutions during the design process rather than being determined in advance. The ZEB tool was systematically used during design and construction to compare various alternatives and lower the carbon footprint. The extent of energy production, selection of materials and design solutions were based on climate performance and contribution to the carbon footprint in the ZEB tool. Early in the process, the calculations were performed based on generic values; project-specific values consecutively replaced these values as decisions were made.

The ZEB Laboratory is a full-scale building encompassing different adaptable façades, components, and technical elements. Its flexibility allows various configurations, technologies, and functions to be explored. The building is used nowadays both as a typical office building and for educational purposes, providing continuous and real-time experimental data necessary to test and validate new technologies and reduce the risk of implementing zero-emission buildings in the future [33].

2.1.2. ZEB ambition

A set of ambitions for the ZEB Laboratory were described in the announcement and asked for in the bid. Apart from the request for flexibility in design and controlled measurement systems, the building was designed to be a model project and achieve ZEB-COM ambition level over 60 years [34,35]. The ZEB ambition levels developed in Norway, in difference from the European nearly zero-energy goals, focus on GHG emissions rather than energy use during the design and operation. The ZEB methodology falls within the scope of (net) zero GHG emission buildings, which is a general term for a range of similar methods and definitions [36]. According to the method, the emissions due to the material production, construction, operation and end-of-life phases must be offset by the equivalent on-site production of renewable energy. Several levels of ambition are defined based on the EN 15978:2011 life-cycle phases that need to be considered for balance. The ZEB-COM ambitious target indicates that the renewable energy produced from the installed technologies in the building or nearby should compensate for the emissions due to material production, construction process and energy for operation and equipment. The GHG calculations must exclude biogenic carbon for such a target since the defined ZEB ambition level does not cover the whole building's life cycle. Biogenic carbon is only included at a ZEB-COME (incl. end-of-life emissions) or ZEB-COMPLETE (all modules A–C in EN 15978:2011) ambition level.

2.1.3. Structure

Materials with low embodied emissions and long service lives have been chosen throughout different building elements to minimise the environmental impact and facilitate the achievement of the ZEB-COM ambition level. The building has a load-bearing structural system made of wood (Fig. 2). Load-bearing vertical elements (columns) are made from glue-laminated timber (glulam), while floors, elevator shafts, and some stiffening elements are made from cross-laminated timber (CLT). The outer walls consist of wooden frames insulated with glass wool. Dark photovoltaic (PV) cells are installed in the roof, the entire southern façade, and partially in the other façades of the building. In the rest façade surfaces, burned wooden cladding is placed externally to create a homogeneous appearance with the PVs.

As far as possible, carbon emissions related to different structure

Fig. 2. An internal photo of the ZEB Laboratory. Photo: Nicola Lolli/SINTEF.

materials were collected from product-specific EPDs. Generic data for materials or products were used when no EPD was available.

2.1.4. HVAC installations

The ZEB Laboratory allows for exploring different ventilation strategies and monitoring user satisfaction and energy consumption. The whole building is prepared for operation and research with natural ventilation, mechanical ventilation or a combination of both. The main staircase extracts air from both the mechanical and natural ventilation solutions. Operation of the windows is also altered; some windows can be manually opened while others have automatic opening systems. Cross ventilation is provided when the windows are opened. The building has, in addition, a central mechanical ventilation system. Four different air distribution systems are applied on each floor, relying all four on the displacement ventilation principle. Heat is provided through a central heat pump with phase change material (PCM) accumulation options, and a heat recovery unit is installed in the exhaust. No cooling system is installed in the building.

For the HVAC systems, only a few products had EPDs at the time of calculation, and generic emission figures were extensively used to calculate the carbon footprint. The project team mapped the material composition of the various components, and the carbon footprint was calculated based on the components' composition. The final manufacturing process was not included, but as most emissions are often associated with raw material production, it was assumed that this provides representative emission data for the HVAC components.

2.1.5. Electrical installations

The building-integrated photovoltaic (BIPV) panels in the roof, façades and an outside pergola allow investigation of the combinations between available local renewable energy production and centralised electricity grid to achieve the zero-emission building requirements [37]. The photovoltaic panels constitute 181 kW installed total effect, respectively 98 on the roof, 70 on the walls and 13 on the pergola. The PCM heat storage installed in the building stores the energy from the BIPV roof and serves as an energy buffer to ensure more efficient use of the sources. Grid integration makes it possible to implement experiments on the interface between buildings (ZEBs) and grids, especially smart grids and district heating and cooling grids.

For electrical installations, none of the products had EPDs; therefore, the material composition was mapped, and generic data was applied to the carbon footprint calculations. The carbon footprint of photovoltaic cells was based on CO_2 declarations provided by the manufacturers (a combination of third-party verified and self-declared values).

2.2. Life cycle assessment (LCA) and greenhouse gas (GHG) emissions

GHG emissions from materials and products used in the construction of the ZEB Laboratory are calculated based on the LCA methodology, as defined in ISO 14040 [38] and ISO 14044 [39]. LCA consists of four stages: i) goal and scope definition, ii) life cycle inventory analysis, iii) life cycle impact assessment, and iv) interpretation. These standards are also the foundation for assessment at both the building and product levels. At the building level, the GHG calculations also follow the methodology developed by the Norwegian Zero Emission Building research centre ([8,40]), as well as using the life cycle module structure defined in the Norwegian standard NS 3720:2018 for GHG calculations of buildings [41]. At the construction product level, the European standard EN 15804:2012 provides core rules for Environmental Product Declarations (EPD) [42,43]. The goal and scope of this study are limited to life cycle production modules A1–A3, addressing the GHG emissions from materials and products used in the ZEB Laboratory.

The results focus on GHG emissions and are quantified as global warming potential (GWP) with the kilogram of carbon dioxide equivalent ($kgCO_2$-eq.) unit, as used in both NS 3720:2018 and EN 15804:2012 standards.

2.2.1. Life cycle inventory (LCI)

The purpose of the life cycle inventory stage is to quantify inputs and outputs for the ZEB Laboratory in line with the goal and scope of the analysis. Here the system boundary is limited to life cycle modules A1–A3 (cradle-to-gate), and the cut-off criteria are aligned with the NS 3720:2018 and EN 15804:2012 standards (5% of mass and energy). The life cycle inventory analysis consisted of two steps. The first step was to quantify the amount and types of materials used in the ZEB Laboratory to get an overview of the physical building. It was an iterative step throughout the construction process, starting with estimates and ending with an exact bill of material (BoM) and appurtenant product specifications. In this analysis, the exact outcome is used. The second step was quantifying the emissions intensity for all materials and products used, i.e. $kgCO_2$-eq. per unit material or product (e.g., per kg, per piece, per meter, etc.). As the goal was to analyse the influence of specific versus generic data, this step required developing two different sets of emission intensities for the physical inventory. The first set of emission factors was as specific as possible, based on Environmental Product Declarations (EDPs) or specific foreground system modelling when EPDs were unavailable. The second set of emission factors was based on generic data.

Data collection for the physical inventory was performed by the entrepreneur responsible for constructing the ZEB Laboratory, Veidekke [44]. The amounts and types of materials are as specific as possible, gathered either from the BIM model or product-specific information. Emission intensities were then gathered from EPDs, where available, and from specific assessments of the foreground system when EPDs were unavailable. These specific assessments were a joint effort between Veidekke and SINTEF. Data collection for the second set of emission factors, with generic values, was performed by SINTEF. Here the main effort was to identify the best connection between specific materials with generic data in the ecoinvent database. The development of both data sets was an iterative process.

2.2.2. Life cycle impact assessment (LCIA)

In the European EPD system, two Life Cycle Impact Assessment (LCIA) methods have been used in different versions of the EN 15804 standard. The EN 15804:2012 + A1:2013 was based on the CML 2001 baseline method [45], and the EN 15804:2012 + A2:2019 is based on the Environmental Footprint (EF) method developed for the European Commission, version 3.0 [46]. Both models use the Intergovernmental Panel on Climate Change (IPCC) model for developing characterisation factors for GWP with a 100-year time horizon (GWP100). The ReCiPe impact assessment method [47] has been used for the generic model, as it provides an up-to-date impact assessment model for multiple impact categories in addition to global warming. However, the ReCiPe also uses the IPCC GWP100 model as a basis for the GWP calculations. In total, three different impact assessments have been used to calculate the results. Although all models are based on the IPCC GWP100 model, this is still a source of uncertainty. This uncertainty cannot be avoided for the generic data without compromising the number of available EPDs. Studies have shown a difference, but the different models in general provide similar results for GWP [48]. It should be noted that for the majority of impact categories, it will not be possible to combine EPDs based on the two different versions of EN 15804.

2.2.3. Uncertainty in GHG calculations

The GHG calculations are based on the same physical materials and products' inventory. However, the specific and generic models use two different approaches for emission inventories and impact assessment modelling. Table 1 shows an overview of the inventory and impact assessment models for the specific and generic modelling. As there are no database requirements for EPDs (as long as they are following the standard), they will, in practice, be based on an unknown combination of LCI databases, in addition to the specific modelling based on ecoinvent version 3.1 for products where there is no EPD available. The

Table 1
LCI and LCIA for the specific and generic inventory data.

Modelling	Physical inventory	Sources for emission inventory	LCIA
Specific LCI	Data from the ZEB Lab.	EPD according to EN15804 + A1:2013 with an unknown mix of background LCI databases	CML 2001 baseline
		EPD according to EN15804 + A2:2019 with an unknown mix of background LCI databases	EF (Environmental Footprint) v3.0
		ecoinvent v3.1 for products and materials where there is no EPD	CML 2001 baseline
Generic LCI	Data from the ZEB Lab.	ecoinvent v3.8	ReCiPe 2016

generic model is based on ecoinvent version 3.8 and ReCiPe 2016.

The table shows that emission intensities are not modelled consistently in the specific model since they are based on multiple sources. This variation will likely increase the uncertainty, both within the specific model and between the specific and generic models. In particular, having two different approaches for EPDs in the specific model increases the uncertainty. However, remodelling may increase consistency but does not necessarily make it more accurate, as this would require replacing the specific foreground system in the EPD with a generic model based on assumptions (shifting source of uncertainty without knowing that it will contribute to reducing it).

2.3. Modelling

2.3.1. ZEB tool (excel)

The contractor company performed the calculations of the life cycle GHG emissions of the ZEB Laboratory with the assistance of SINTEF's in-house experts. The results were structured using an Excel-based tool (ZEB tool v.1) developed by the Norwegian Research Centre on Zero Emission Buildings (FME ZEB) [31]. In its framework, the tool follows the general life cycle assessment methodology defined in ISO 14044:2006 and the methodology for evaluating the environmental performance of buildings outlined in EN 15978:2011. The basis for the calculation results was the GHG emissions from EPDs for construction products marketed in Norway. An EPD database of the potential materials and products was created and used for calculations and decision-making. When the supplier of specific elements was unknown, or the EPD data was unavailable, emission intensities were calculated based on supplier documentation and life cycle inventory data from ecoinvent v3.1. Since the model is mainly based on EPD data, the uncertainty in products is not captured while using the tool. Biogenic carbon content related to building products with bio-based raw materials is not considered in the GHG calculations since the system boundaries do not include end-of-life modules. The carbonation of concrete has not been counted in the GHG calculations of the ZEB Laboratory.

In the tool interface, product stage emissions (M) are categorised and assessed according to the building element categories specified in NS 3451:2022 [49]. In addition, the emissions for the construction and transport phases (C) and the estimated energy consumption and production in a life-cycle perspective (O) are calculated separately to reach the ZEB-COM ambition level.

2.3.2. Ecoinvent database (SimaPro)

The carbon footprint of the materials and products applied in the ZEB Laboratory was re-calculated with SimaPro, a software developed to assess the environmental impacts based on the LCA concept [50]. In the software, the building was modelled using only generic life cycle inventory data from the ecoinvent database v3.8. The unit products were first grouped according to the ecoinvent material categories; then, the building was modelled according to the building elements (in analogy with the ZEB tool). This model allows the results of both versions to be more easily compared.

Some recalculations were necessary to insert the correct quantities in the software version. Specific EPD products have different declaration units compared to the ecoinvent database. Therefore, the right quantities were inserted in the software by converting them into ecoinvent functional units utilising density, weight, dimensions, or other information extracted from the EPDs. In this context, some products of the same category, e.g., various rock wool products declared in areal units, were merged into one generic element expressed in weight when modelled in the ecoinvent model. In a few cases, compound products were not found in the ecoinvent database. Such products were created manually in the software using ecoinvent-based materials and the composition percentage specified in the corresponding EPDs.

3. Results

3.1. Building elements

The embodied emissions of the products applied in the ZEB Laboratory according to the main building categorisation for the two methods explained above are given in Table 2.

According to the ZEB tool, GHG emissions per A1–A3 modules (product stage) for the ZEB Laboratory are about 4.0 kgCO$_2$eq/m^2/year. This ratio is the lowest among other new projects of zero-emission buildings (ZEBs) in Norway, where the same tool has also been applied for emission estimations [8]. The result highlights the significance of thoroughly using decision-making tools or material emission intensities during the design phase to compare and select products with a lower carbon footprint.

The emissions for material production (M), corresponding to product phases A1–A3 of EN 15978:2011, are extracted from the Excel-based calculations and compared with SimaPro software-remodelled version. The diagrams showing the impact of the building elements in the total assessment are given in Fig. 3.

As can be easily seen from the figure, the category with the highest fluctuation (316%) is category 4 – Electric Power. This difference derives from the remodelling of PV panels (almost 1000 m^2 in the building) which has an impact almost four times higher in the ecoinvent version than the actual PV data calculated from the supplier. A more explanation of such fluctuation is given in paragraph 3.2. Otherwise, it must be noted that most of the emissions of the elements in categories 3 – HVAC, 4 – Electric power (except PVs) and 5 – Telecommunication and Automation are calculated based on the ecoinvent database in both models. Therefore, the comparison is more relevant for category 2 – Building, where the embodied energy of most products in the Excel tool was calculated from their respective EPDs.

Fig. 4 shows the impact of the compounding elements of category 2 – Building in more detail.

The emissions of the building structural components when applying the ecoinvent generic data are 16% higher than the one calculated with the ZEB tool. Almost all the compound categories in category 2 – Building give higher values when ecoinvent is used, with the highest absolute difference noted in category 21 – Groundwork and Foundation. Such an outcome is primarily linked with the unit emissions of the reinforcement steel used only in the foundations of the building. According to the Norwegian EPD (NEPD), the carbon footprint for producing 1 kg of reinforcement steel in Norway is 0.3 kgCO$_2$-eq. Meanwhile, steel production in the European market (RER) has an environmental cost of 2.1 kgCO$_2$-eq. in the ecoinvent database. The significant difference is associated with the fact that steel production in Norway is supplied mainly from recycled content, and the primary energy source for metallurgic industries is hydropower. The differences in

Table 2
The embodied emissions for the construction of ZEB Laboratory according to building elements.

CODE	BUILDING ELEMENT	ZEB tool		ecoinvent		
		A1–A3 [$kgCO_2$-eq.]	[%]	A1–A3 [$kgCO_2$-eq.]	[%]	ecoinvent/ZEB tool [%]
21	Groundwork and Foundations	43180	10.2%	61127	8.9%	142%
22	2Superstructure	24884	5.9%	28347	4.1%	114%
23	Outer walls	62717	14.9%	60257	8.8%	96%
24	Inner walls	27199	6.5%	28079	4.1%	103%
25	Floor Structure	46935	11.1%	55957	8.2%	119%
26	Outer Roof	23236	5.5%	28261	4.1%	122%
27	Fixed Inventory	1077	0.3%	1698	0.2%	158%
28	Stairs and Balconies	6459	1.5%	8564	1.3%	132%
2	**BUILDING**	**235686**	**55.9%**	**272289**	**39.9%**	**116%**
31	Sanitary	9312	2.2%	10063	1.5%	108%
32	Heating	9884	2.3%	10008	1.5%	101%
33	Fire Safety	9343	2.2%	10969	1.6%	117%
36	Ventilation and Air Conditioning	43289	10.3%	33067	4.8%	76%
3	**HVAC**	**71828**	**17.0%**	**64107**	**9.4%**	**89%**
41	Basic Installation for Electric Power	7830	1.9%	9689	1.4%	124%
43	Low Voltage Power	17262	4.1%	27604	4.0%	160%
44	Lighting	7292	1.7%	8224	1.2%	113%
45	Electric Heating	5	0.0%	11	0.0%	216%
46	Standby Power	231	0.1%	272	0.0%	118%
49	Other (PVs)	73136	17.3%	288522	42.2%	395%
4	**ELECTRIC POWER**	**105756**	**25.1%**	**334322**	**48.9%**	**316%**
51	Basic Installation for Tele. and Automation	725	0.2%	852	0.1%	118%
52	Integrated Communication	2082	0.5%	3930	0.6%	189%
54	Alarm and Signal	212	0.1%	248	0.0%	117%
56	Automation	132	0.0%	167	0.0%	126%
5	**TELE. AND AUTOMISATION**	**3151**	**0.7%**	**5197**	**0.8%**	**165%**
62	Passenger and Goods Transport	5239	1.2%	7283	1.1%	139%
6	**OTHER INSTALLATIONS**	**5239**	**1.2%**	**7283**	**1.1%**	**139%**
	TOTAL ZEB-LAB. [$kgCO_2$-eq.]	**421660**	**100.0%**	**683200**	**100.0%**	**162%**
	TOTAL ZEB-LAB. [$kgCO_2$-eq./m^2]	242.1		392.2		
	TOTAL ZEB-LAB. [$kgCO_2$-eq./m^2/year]	4.0		6.5		

other building categories are linked mainly with the wooden products used extensively in the building. The highest absolute difference related to the application of wooden products is noticed in category 25 – Floor structure because of the elements designed in cross-laminated timber, which have a higher impact in the ecoinvent database (137 $kgCO_2$-eq./m^3) than in the EPD (60 $kgCO_2$-eq./m^3). The other alterations connected with the other primary constructive materials will be commented on in the following paragraph.

3.2. Building materials

Another sorting of components and products that constitute the ZEB Laboratory is done according to the material category. The embodied emissions and the contribution of each material category are given in Table 3. The differences between the two models are visualised graphically in Fig. 5.

From comparing the two models, certain materials have a higher impact when the ZEB tool is applied, while others give a higher number in the ecoinvent model. The remarks for such alterations concerning the primary materials used in the building are given:

- **Technical equipment** is the highest contributor to embodied emissions during the construction of the ZEB Laboratory. The category comprises building installations such as appliances, heat pumps, hot water tanks, automatic ventilation engines, window-opening motors, elevators etc. However, the big difference between the two models (324%) is not a result of such installations since the ecoinvent database has been used for most technical products. Instead, the huge difference derives from the remodelling of PVs, which constitute most of the building's external envelope. A total of 701 monocrystalline panels of different types and shapes (total area 963 m^2) are installed for a total power of 184 kWp and an expected yearly PV production of 156 MWh. The estimated emissions performed by the contractor company are achieved by multiplying the unit emission for 1 kW-peak ($kgCO_2$-eq./kWp) provided by the producer with the total peak power of the PV panels. However, the ecoinvent database does not offer an excessive variety of PV models and the emissions are given for one m^2 panel production. Therefore, one single input representing the monocrystalline panels has been chosen for the entire area covered with PVs. Two different mounting systems have been selected for the façade and roof installations. The overall emissions from the ecoinvent model are almost four times higher than the ZEB tool version. In this model, the result was obtained by multiplying the unit emission for the production of one m^2 panel ($kgCO_2$-eq./m^2) with the total area of the PV panels. The considerable difference is attributed to the photovoltaic products in the ecoinvent database, which are outdated and do not encompass the improvements in the sector regarding energy production efficiency and environmental impact [51].

- **Wood** is the main structural element of the building, and its products are present in all main building elements. The results show that wooden products in diverse building functions have a higher carbon footprint when calculated with generic ecoinvent data, although there is a notable variation between the products. The highest oscillation is observed for glue-laminated or cross-laminated timber elements that have an impact up to 2 times higher when using the ecoinvent data. Other wooden products with a significant difference between the two models are window frames and structural sawn wood, which are widely used in the structure. A similar trend is also noted in other studies that compare specific EPDs with generic databases for a wide variety of wooden construction products [25,52].
- **Metal** is the category with the second highest environmental impact in the building. The category primarily consists of various steel products used in the structural elements, inner and outer walls, aluminium products, electrical installations, etc. In specific cases,

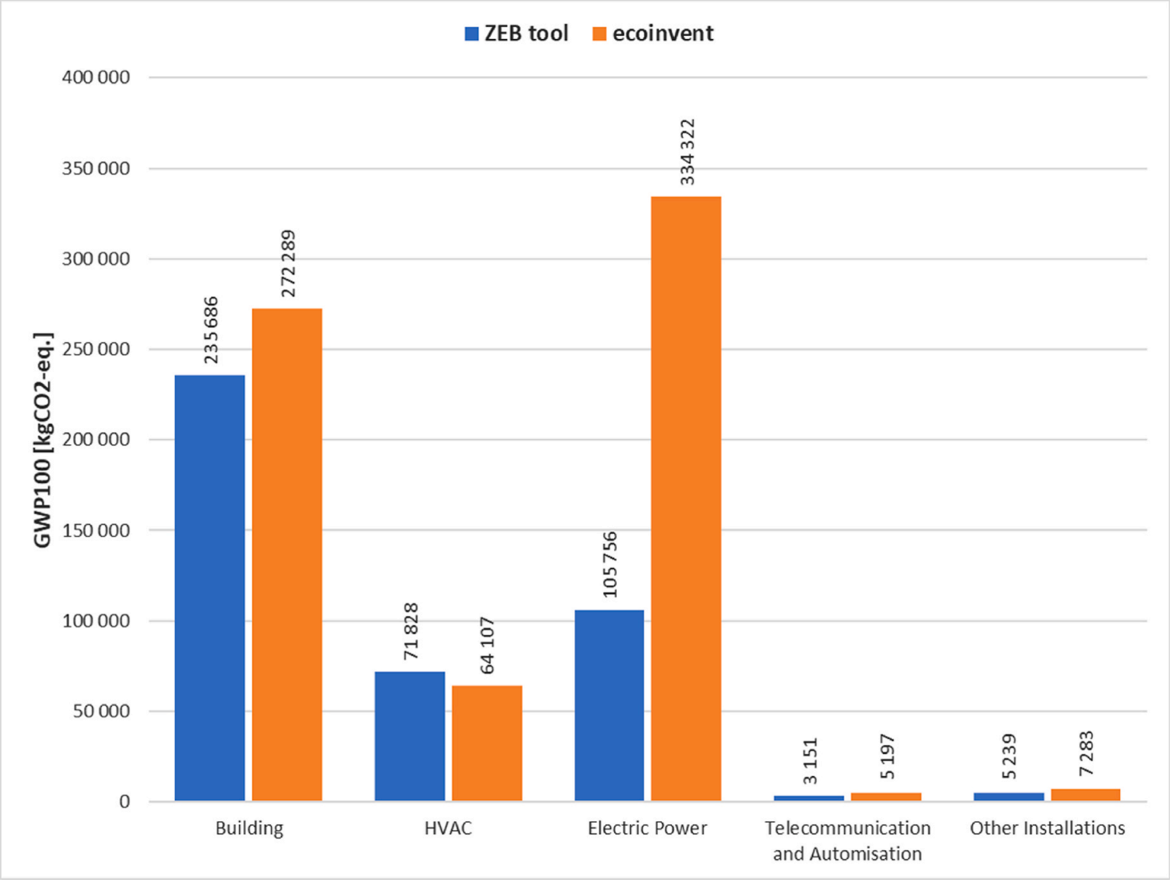


Fig. 3. Diagrams of the embodied emissions for the construction of ZEB Laboratory according to building elements.

generic products are set in both models. Nevertheless, up to 50% difference in the emissions' value is due to the high presence of recycled content and electricity factors in the Norwegian metallurgic products when NEPD products are compared with European ecoinvent equivalents.

- **Concrete** is primarily used in the foundations of the building, and the difference between the two versions is around 11%. It is worth mentioning that the concrete products in the ecoinvent model were not selected directly from the database but were created manually as compound products with ecoinvent aggregates and quantities/ratios from the EPDs.
- **Insulation** products are extensively present in all building elements, such as foundations, outer and inner walls, floors and the roof, and among the materials with the most available EPDs by the producers. From the facing of the two models, in difference with the other primary materials, it is observed that the impact when using ecoinvent data is smaller than the version with EPDs. This result is derived because, in the ecoinvent catalogue, the impact for most insulation products is declared for their weight (typically kg). In contrast, the EPDs express the impact of a finished product intended for the market (with a defined width) and typically areal (m^2) declaration unit. Therefore, the conversion of quantities does not comprise the procession into thin-layer products. Moreover, various insulation products with different characteristics were represented with a unique material in the ecoinvent model, excluding the importance of the scaling factor for more sophisticated products.
- **Coverings** consist mainly of gypsum plasterboard or supporting systems applied to complete the inner walls or floor elements. Also, for such elements, the impact from the ecoinvent database is around 70% of the values obtained from the EPDs. In analogy with the insulation products, the lower ecoinvent values are primarily because of the grouping of different advanced products in only one simple in the ecoinvent database and the conversion of units when remodelled (gypsum plasterboard is declared in kg at the generic database and m^2 at the EPDs).

3.3. Relationship between different grouping categories

3.3.1. ZEB tool (excel)

The comments related to the building elements of category 2 – Building and the materials of this category are understood easier when the two classifications are faced with each other to see the links between them. The flow that shows the relation between the two different categorisation systems in the ZEB tool model is given in Fig. 6.

The figure gives a better overview of the connection between the two categories. Emissions from 21 – Groundwork and Foundations mainly consist of the concrete and insulation elements, while the materials with the highest impact in 22 – Superstructure are wood and metals. Windows are responsible for almost half of the emissions in 23 – Outer Walls, while the contribution in the other building elements is due to a combination of diverse materials.

3.3.2. Ecoinvent database

The same confrontation has been done for the ecoinvent database model. The Sankey diagram of emissions flow between the two categories is visualised in Fig. 7.

From the figure, in difference with the ZEB tool model, it can be noticed that not only concrete and insulation but also metals, specifically reinforcement steel, influence the emissions of 21 – Ground and Foundations. Comparing the two figures shows that emissions from 25 – Floor Structure in the ecoinvent model are mainly due to the use of wood (glue-laminated timber). In contrast, the coverings layers of the floors

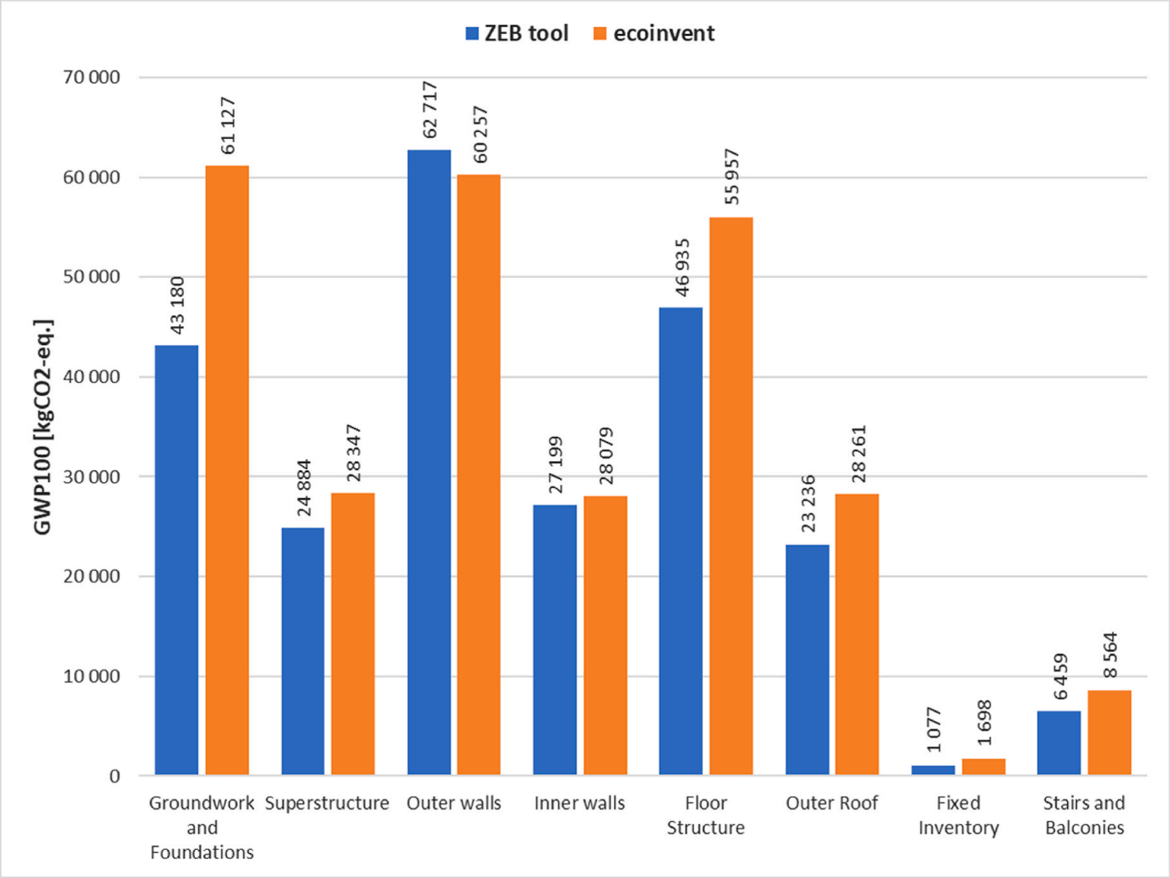


Fig. 4. Diagrams of the embodied emissions of the elements of category 2 – Building.

have the largest impact in the ZEB tool model. The other building elements show the same flow pattern when comparing diagrams.

Table 3
The embodied emissions for the construction of ZEB Laboratory according to material categories.

MATERIAL CATEGORY	ZEB tool		ecoinvent		
	A1–A3 [kgCO$_2$-eq.]	[%]	A1–A3 [kgCO$_2$-eq.]	[%]	ecoinvent/ ZEB tool [%]
Bitumen	**3976**	0.9%	**4746**	0.7%	**119%**
Ceramics	**914**	0.2%	**542**	0.1%	**59%**
Cladding	**4969**	1.2%	**8473**	1.2%	**171%**
Concrete	**21535**	5.1%	**23865**	3.5%	**111%**
Coverings	**32871**	7.8%	**22956**	3.4%	**70%**
Doors	**3028**	0.7%	**3458**	0.5%	**114%**
Flooring	**2012**	0.5%	**4324**	0.6%	**215%**
Furniture	**375**	0.1%	**237**	0.0%	**63%**
Glass	**13956**	3.3%	**14182**	2.1%	**102%**
Insulation	**43348**	10.3%	**34637**	5.1%	**80%**
Metals	**68998**	16.4%	**102741**	15.0%	**149%**
Paints	**3156**	0.7%	**2483**	0.4%	**79%**
Plastics	**18509**	4.4%	**17771**	2.6%	**96%**
Sealing	**145**	0.0%	**67**	0.0%	**47%**
Technical	**94615**	22.4%	**306200**	44.8%	**324%**
Ventilation	**28947**	6.9%	**27907**	4.1%	**96%**
Windows	**30917**	7.3%	**30902**	4.5%	**100%**
Wood	**49390**	11.7%	**77708**	11.4%	**157%**
TOTAL ZEB-LAB.	**421660**	100.0%	**683200**	100.0%	**162%**

3.4. *General overview*

As stated above, when there was unknown or unavailable EPD information for certain products, the results in the ZEB tool were based on the ecoinvent database v3.1. However, comparing the results from the two models is more accurate when these products without EPD data are excluded from the main results in order to achieve the article's objectives. A total inventory of product quantities grouped into building elements, material categories and the respective emission factors for the products with EPDs is given as a supplementary file.

An overview of emissions based on the sources used for both models is given in Table 4.

As the table notes, the embodied emission ratio between the products with EPDs and their remodelled equivalents utilising ecoinvent data is 180.8% higher when ecoinvent is used. However, such a difference is heavily impacted by the remodelling of the PVs, as discussed in paragraph 3.2. Therefore, another general comparison has been made by excluding the category of solar panels 49 – Other (PVs) from the main results for a better overview and general assessment of the findings (Table 5).

The emissions without the PVs impact show that the difference between the ecoinvent products and their corresponding EPD numbers is 15%. This ratio is the same when generally comparing category 2 – Building (16%) since that is the category where most of the EPD data were used. To provide a perspective on the difference, we can compare it to the recommendations of the national emissions databases for construction recently launched in Finland and Sweden, which apply a conservative conversion factor of 1.2 and 1.25 to the average EPD values when creating the generic database. This conservative factor was also introduced in Norwegian legislation in 2022 [5].

Another difference (8.2%) is noticed when ecoinvent products are

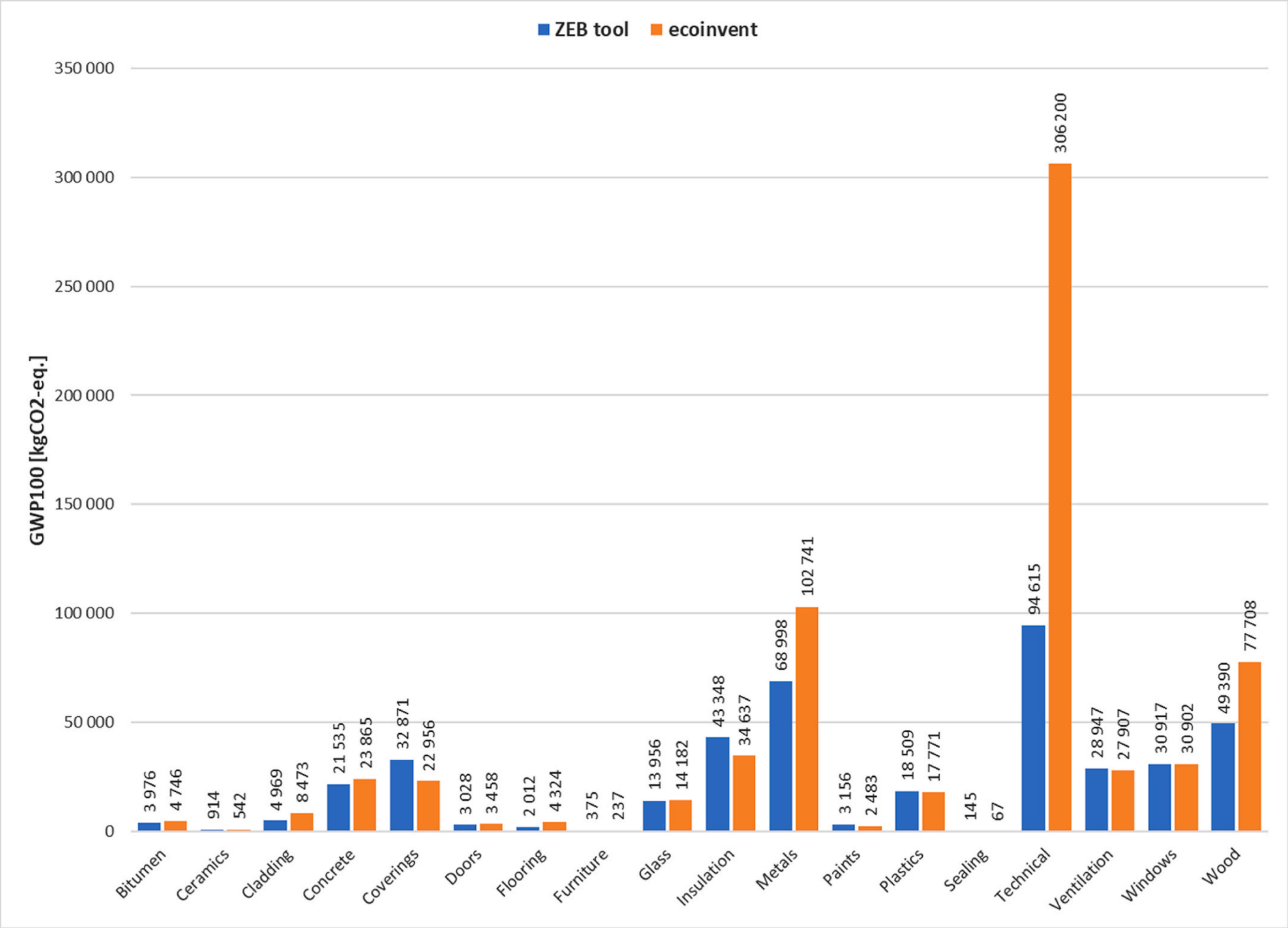


Fig. 5. Diagrams of the embodied emissions for the construction of ZEB Laboratory according to material categories.

used in both models. The ratio is likely due to different versions of the ecoinvent databases.

3.5. Uncertainty in GWP and correlation between GWP and other LCIA categories

3.5.1. Uncertainty in GWP through Monte Carlo simulation

The Monte Carlo simulation (MCS) function implemented in SimaPro has been used to analyse the generic ZEB Laboratory model (based on ecoinvent v3.8). This approach provides a visual understanding of the model uncertainty and is used to investigate selected building elements' contribution to the variability in the GWP results in the generic mode. The parameter uncertainty was evaluated for 1000 simulation runs and a stop factor of 0.005.

Fig. 8 shows the MCS results for the generic model of the entire ZEB Laboratory. The lines in the middle show the mean (dashed line) and median values, whereas the outer lines show the 95% confidence interval. A visual inspection of the figure indicates that the results are similar to a normal distribution but with the upper bound slightly higher than the lower bound. Comparing the results with the GWP value from the ZEB tool, the ZEB tool uncertainty results are outside of the 95% confidence interval. The comparison indicates a significant difference between the two models. However, due to limitations in the Monte Carlo simulation, we cannot state that there is a statistically significant difference [53].

Fig. 9 shows the uncertainty results of building element 21 – Groundwork and Foundations, which contributes to 9.6% of the total GWP for the generic model of the ZEB Laboratory. A visual inspection indicates that the confidence interval and distribution shape is similar to that of the entire building but with the upper bound closer to the median than for the entire building.

The results presented in sections 3.1 and 3.2 demonstrated that technical installations, in general, and PVs, in particular, significantly contribute to the GWP results. Figs. 10 and 11 visualise the MCS results for the ZEB Laboratory separated from the photovoltaics. The first figure shows the uncertainty results of the ZEB Laboratory without photovoltaics (without building element 49 – Other (PVs)), and the second one visualises the uncertainty only for photovoltaics (only building element 49 – Other (PVs)). The figures indicate that the upper bound of the confidence interval is significantly higher for the PVs than for the rest of the building. This result supports our assessment that the PV data have a higher uncertainty. Moreover, the uncertainty results from the ZEB tool with EPD data are still not within the 95% confidence for the ZEB Laboratory, even in the model without PVs.

Fig. 12 shows the MSC results for the ZEB Laboratory excluding all building elements related to category 4 – Electric Power. The results are close to a normal distribution, with upper and lower bounds for the confidence interval relatively equal distances to the mean and median. Fig. 13 visualises the MSC results of the electric power installations without photovoltaics (building elements 41–48 only). The uncertainty results are similar to the rest of the building. This conclusion again indicates that photovoltaics significantly contributes to the uncertainty in the generic model of the ZEB Laboratory.

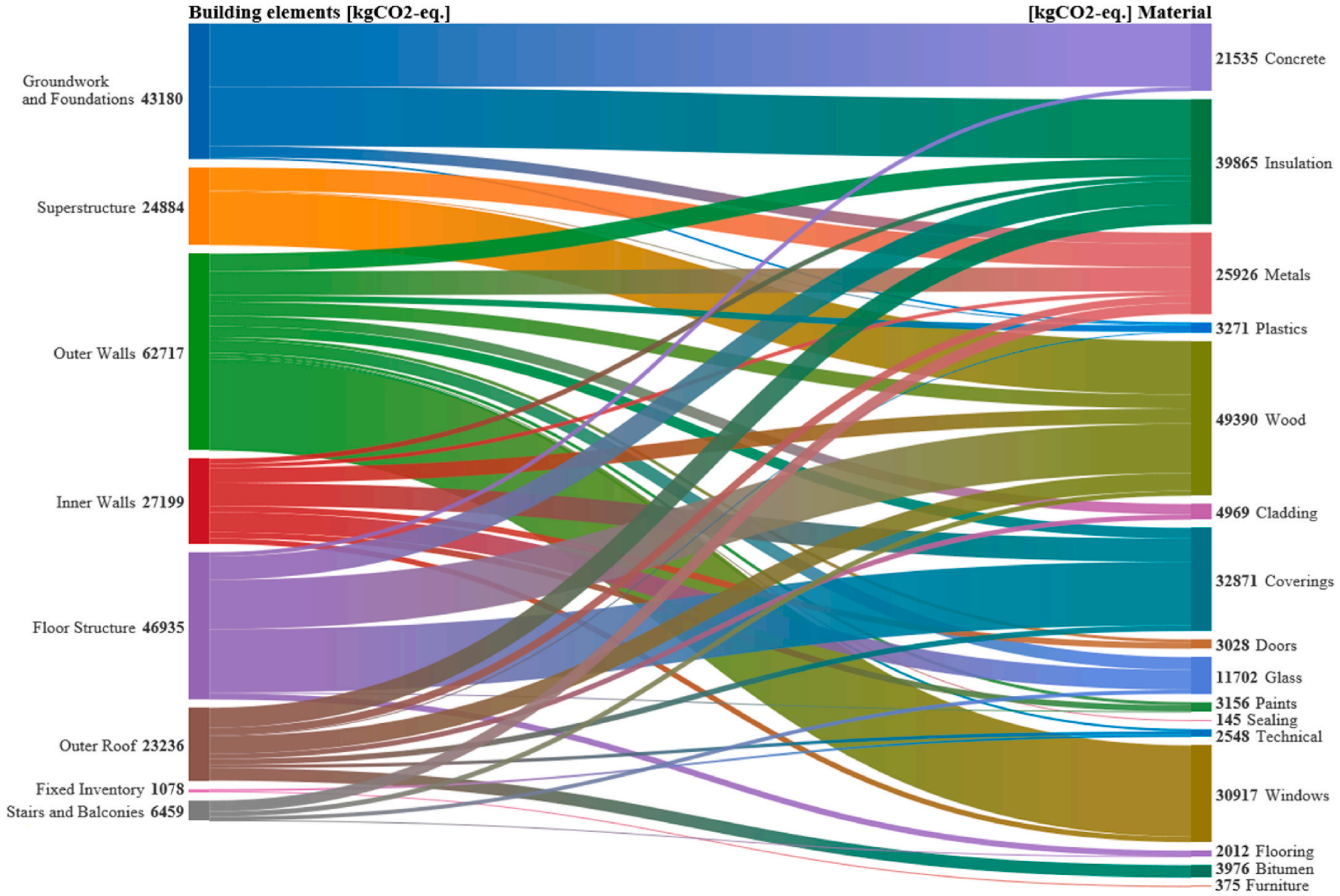


Fig. 6. Relationship of the emissions between the building element and material categorisation systems in the ZEB tool model.

3.5.2. Correlation between LCIA methods

There are two main challenges regarding LCIA when comparing the specific and generic models of the ZEB Laboratory. The first challenge is that different impact assessment methods have been used to calculate the GWP results for specific and generic models. The second challenge is that the results have been calculated only for GWP.

The first challenge is the variation in LCIA methods used to calculate the GWP. Two LCIA methods have been used in the specific model (both based on CML 2001 baseline) and one in the generic model (ReCiPe 2016), as described in sections 2.2.2 and 2.2.3. Because of this, the GWP results are not methodologically consistent. Avoiding this situation is a particularly complicated challenge for all models using EPDs since they provide LCIA results of the product's material composition but do not include the underlying inventory. To explore the potential significance of different methods, the GWP has been calculated for the generic model using both ReCiPe and CML.

The result of the calculation shows that the GWP results calculated with ReCiPe are consistently 2%–7% higher than those from CML. The GWP calculated with ReCiPe is 2–4% higher than using CML for all building elements, except for building element 32 – Heating. For the latter, the difference is 7%. The ratios indicate a slight and consistent difference, with ReCiPe providing higher GWP values than CML. However, this difference is so low that it does not explain the differences between the two models, as presented in section 3.1.

3.5.3. Correlation between LCIA impact categories

The ZEB Laboratory has been designed to have low embodied GHG emissions, which means that there is an inherent risk of shifting the problem from global warming towards other environmental impact categories. However, an advantage of using ReCiPe 2016 as the LCIA method is that it makes it possible to calculate results for other impact categories than GWP with an impact assessment model that is more up-to-date than the CML 2001 baseline. Fig. 14a–g shows the LCIA results for 18 different impact categories, with results for all building elements (seven in total) where at least one of the 18 LCIA indicators results is above 10% of the total impact. 16 of the 23 building elements have no LCIA indicator results exceeding 10% of the total impact.

A visual interpretation of Fig. 14 indicates that there is a degree of correlation between the 18 impact categories in ReCiPe. However, significant individual differences exist across the various impact categories and building elements.

Analysing the Pearson correlation across the LCIA impact categories reveals a correlation between specific impact categories, as shown in Table 6. In particular, there is a strong correlation (>0.8) between Global warming and eight other impact categories, and between Mineral resource scarcity and six other impact categories. Furthermore, these correlations are mutually exclusive. In addition, there are two impact categories with a low correlation to any other impact category: Land use and Human carcinogenic toxicity. It means that two indicators are good proxies for covering 16 of the 18 impact categories, but it risks missing significant impacts in Land use and Human carcinogenic toxicity.

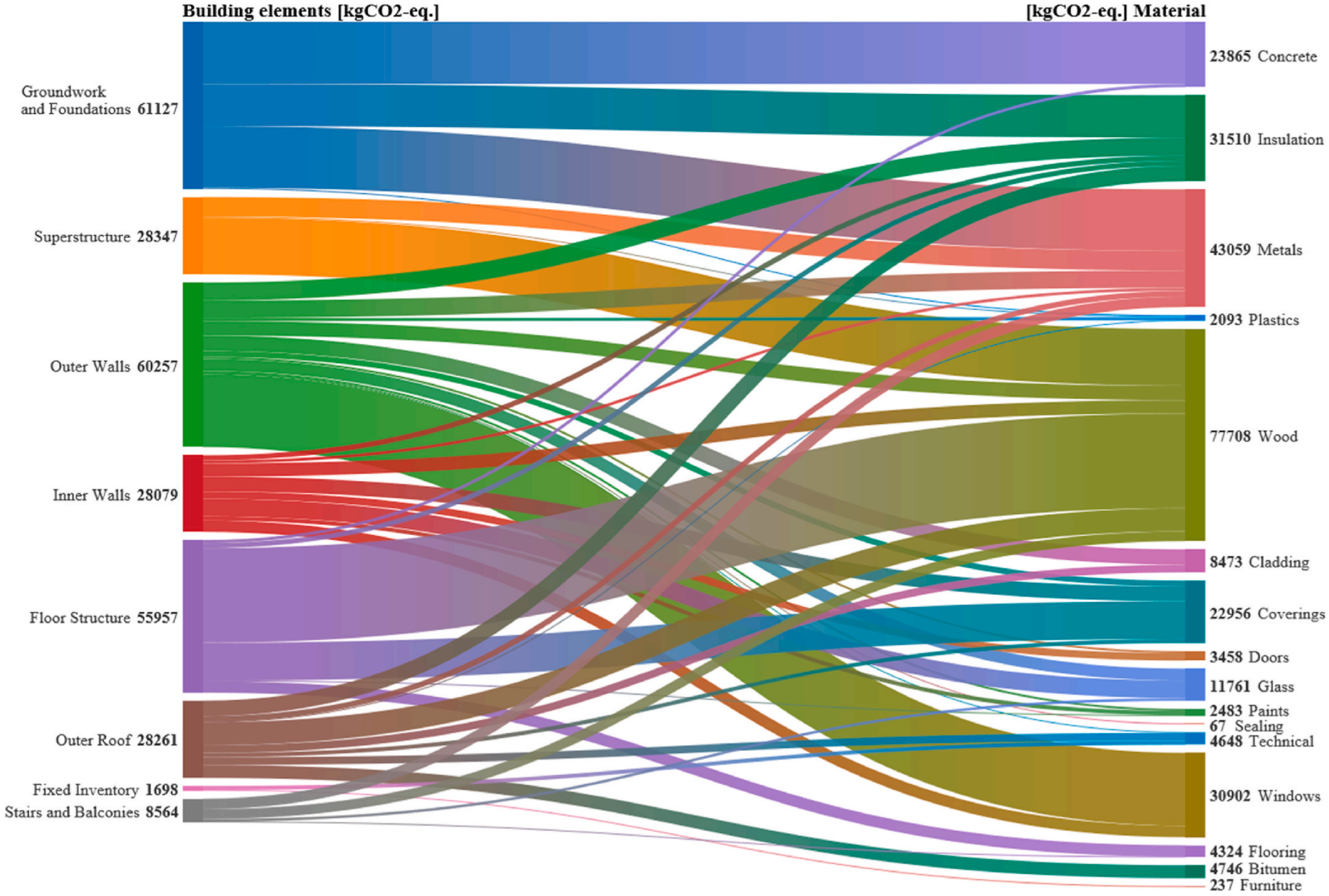


Fig. 7. Relationship of the emissions between the building element and material categorisation systems in the ecoinvent model.

Table 4
The embodied emissions for the construction of ZEB Laboratory according to the data source.

ZEB tool	A1–A3 [kgCO$_2$-eq.]	[%]	ecoinvent v3.8	A1–A3 [kgCO$_2$-eq.]	[%]	ecoinvent/ZEB tool [%]
EPD	**313129**	74.3%	**ecoinvent (EPD-eq.)**	**566127**	82.9%	**181%**
ecoinvent v3.1	**108531**	25.7%	**ecoinvent**	**117073**	17.1%	**108%**
TOTAL ZEB-LAB.	**421660**	100.0%	**TOTAL ZEB-LAB.**	**683200**	100.0%	**162%**

Table 5
The embodied emissions for the construction of the ZEB Laboratory according to the data source, excluding category 49 – Other (PVs).

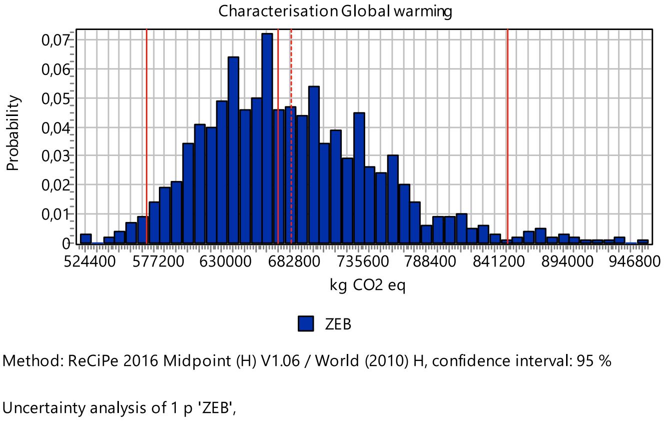
ZEB tool	A1–A3 [kgCO$_2$-eq.]	[%]	ecoinvent v3.8	A1–A3 [kgCO$_2$-eq.]	[%]	ecoinvent/ZEB tool [%]
EPD	**242469**	69.6%	**ecoinvent (EPD-eq.)**	**279940**	70.9%	**115%**
ecoinvent v3.1	**106055**	30.4%	**ecoinvent**	**114737**	29.1%	**108%**
ZEB-LAB. (excl. PVs)	**348524**	100.0%	**ZEB-LAB. (excl. PVs)**	**394677**	100.0%	**113%**

The above results have been calculated for one single LCA model of one single case building, and further research is needed to see if these findings are generalisable.

3.6. Discussions and recommendations for future work

Requirements for a GHG declaration when constructing new residential blocks and commercial buildings in Norway have put the producers of materials, construction companies and involved specialists in a new situation. The calculations must be prepared early in the design phase, and the results should be actively improved to reduce emissions during the design and construction process. For such estimations, where the final materials and products are not defined yet, a generic emissions intensity database must be developed and systematically improved as more information and advanced tools become available. Such a database can be created at a national or regional level using average EPD values for construction products or through well-known generic databases.

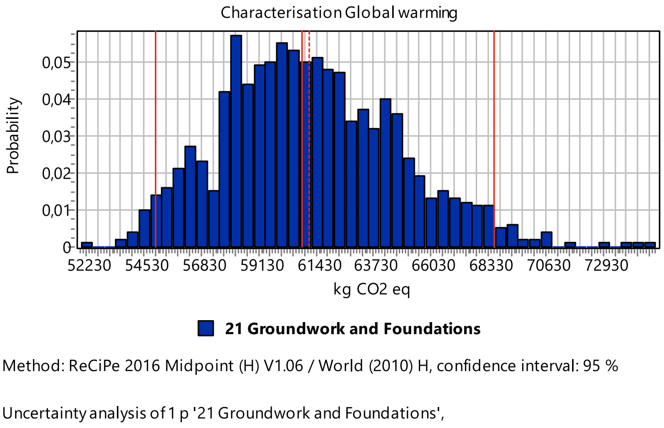
The comparison between an EPD-based and a generic ecoinvent model was limited to the production modules A1–A3 as the stage with the highest impact during the construction of ZEB Laboratory and where most of the specific EPDs can be found. However, the calculations provided by the contractor company also include modules A4, A5, B4 and B6, which are necessary to reach the ZEB-COM balance. The results would be complete if all of the above modules were considered in the



Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 95 %

Uncertainty analysis of 1 p 'ZEB',

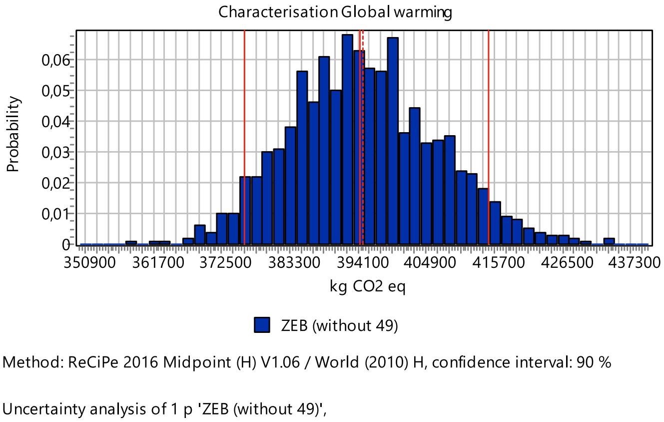
Fig. 8. GWP uncertainty for the ZEB Laboratory (modelled with ecoinvent v3.8).



Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 95 %

Uncertainty analysis of 1 p '21 Groundwork and Foundations',

Fig. 9. GWP uncertainty for 21 – Groundwork and Foundations of the ZEB Laboratory.

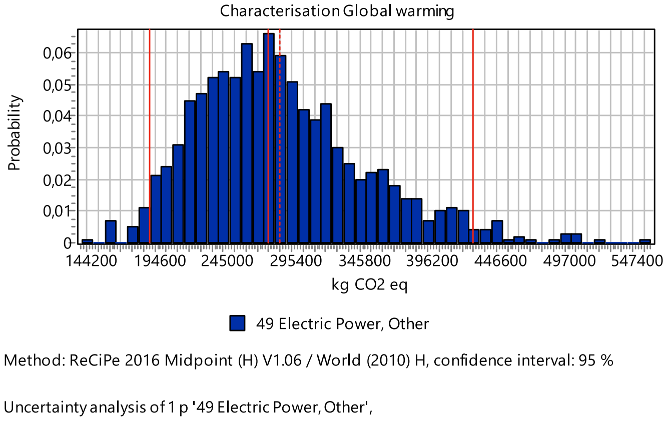


Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 90 %

Uncertainty analysis of 1 p 'ZEB (without 49)',

Fig. 10. GWP uncertainty for the ZEB Laboratory, excluding category 49 – Other (PVs).

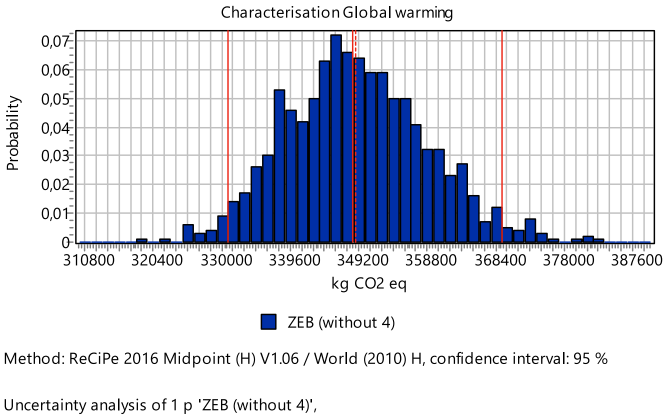
assessment, especially the module regarding operational energy (B6). The total energy consumption of the building and the total generated energy from the renewables play a significant role in the decarbonisation process, and the comparison between generic and specific energy databases requires further investigation. Furthermore, according to the recent requirements of the Norwegian standard TEK17, the GHG account for new building materials must at least include modules A1–A4, B2 and B4. Hence, the calculations and the comparison would be complete when module B2 (maintenance) is also included in both models.



Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 95 %

Uncertainty analysis of 1 p '49 Electric Power, Other',

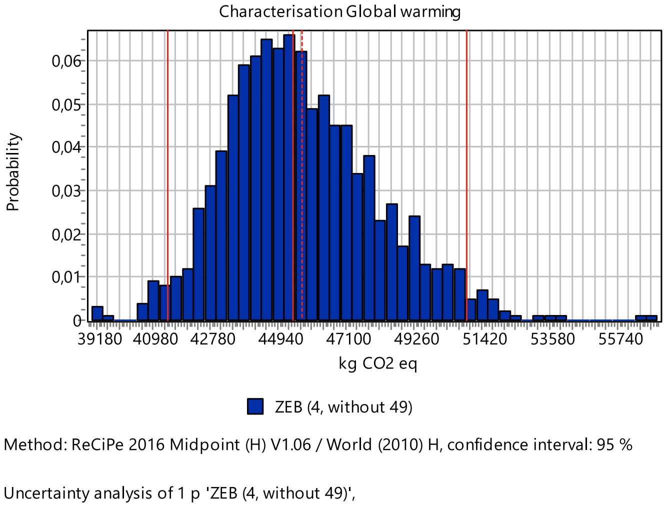
Fig. 11. GWP uncertainty only for category 49 – Other (PVs) of the ZEB Laboratory.



Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 95 %

Uncertainty analysis of 1 p 'ZEB (without 4)',

Fig. 12. GWP uncertainty for the ZEB Laboratory, excluding category 4 – Electric Power.



Method: ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, confidence interval: 95 %

Uncertainty analysis of 1 p 'ZEB (4, without 49)',

Fig. 13. GWP uncertainty for 4 – Electric Power of the ZEB Laboratory, excluding category 49 – Other (PVs).

The PVs in the ecoinvent database have a high carbon footprint and low efficiency compared to actual products found in the market. An update of the generic databases with the recent developments would

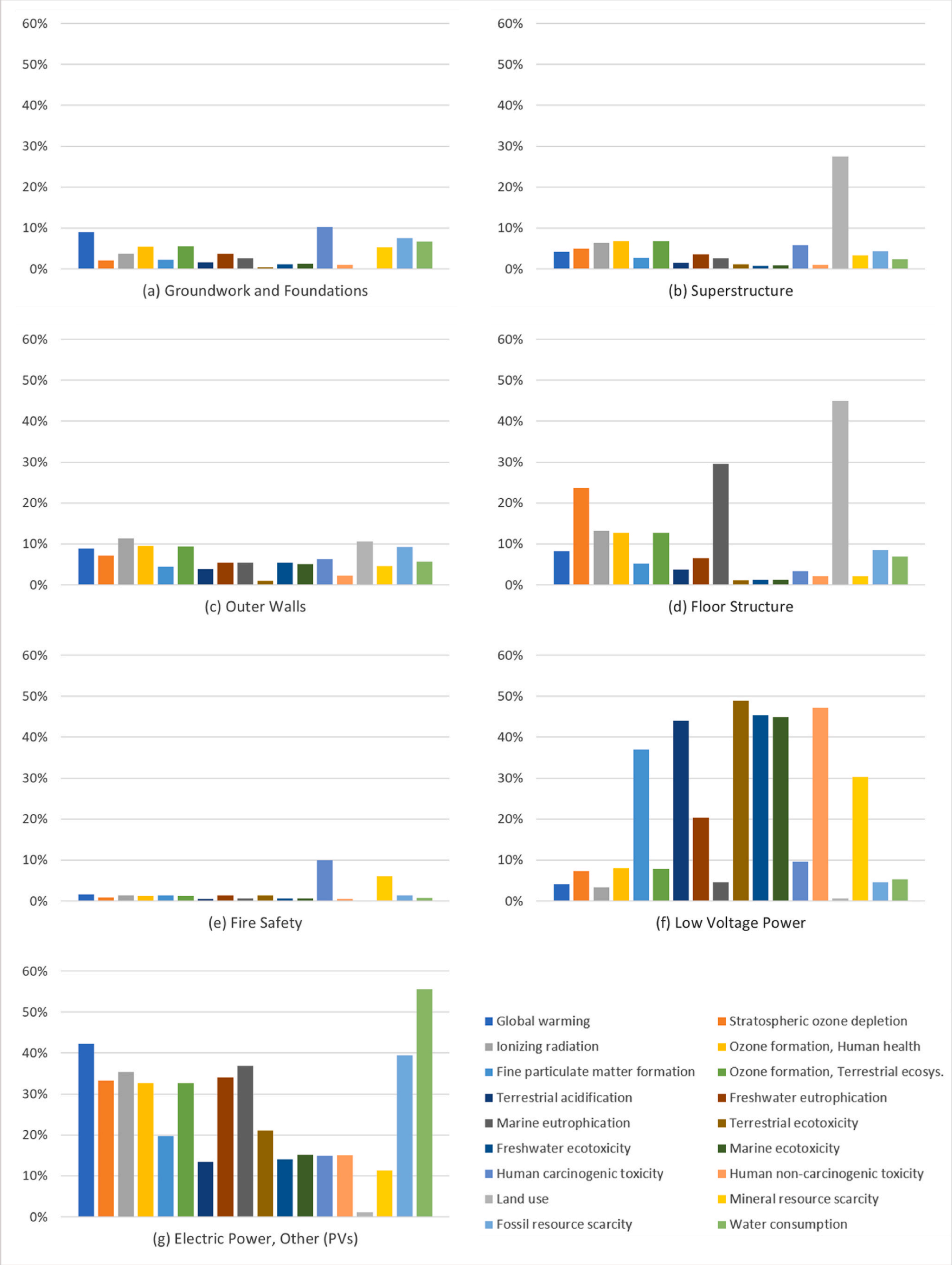


Fig. 14a. a-g. LCIA per building elements where at least one LCIA indicator result is above 10% of the total.

Table 6
Correlation between LCIA indicator results.

Impact category	Pearson correlation			
	Global warming	Mineral resource scarcity	Land use	Human carcinogenic toxicity
Global warming	**1**	0.31	0.12	0.69
Stratospheric ozone depletion	**0.88**	0.31	0.49	0.54
Ionising radiation	**0.96**	0.26	0.32	0.62
Ozone formation, Human health	**0.97**	0.40	0.31	0.68
Fine particulate matter formation	0.46	**0.96**	-0.01	0.56
Ozone formation, Terrestrial ecosystems	**0.97**	0.39	0.31	0.68
Terrestrial acidification	0.26	**0.97**	-0.06	0.47
Freshwater eutrophication	**0.88**	0.70	0.06	0.71
Marine eutrophication	**0.85**	0.23	0.51	0.48
Terrestrial ecotoxicity	0.35	**0.95**	-0.11	0.47
Freshwater ecotoxicity	0.26	**0.96**	-0.11	0.44
Marine ecotoxicity	0.28	**0.96**	-0.11	0.46
Human carcinogenic toxicity	0.69	0.63	0.01	**1**
Human non-carcinogenic toxicity	0.26	**0.97**	-0.10	0.45
Land use	0.12	-0.09	**1**	0.01
Mineral resource scarcity	0.31	**1**	-0.09	0.63
Fossil resource scarcity	**1**	0.32	0.14	0.68
Water consumption	**0.99**	0.32	0.04	0.64

Note: Cells marked with grey indicate a strong correlation (>0.80) between the two intersecting impact categories.

facilitate estimating and comparing the emission from the operational and generated energy and the payback time when implying different databases.

In the ZEB tool model, most of the data for construction materials were obtained from specific EPDs, while when the EPD data was unavailable, the emission intensities were taken from the ecoinvent database. Market products without EPDs were mostly from the HVAC, electric, telecommunication and automation installations, which highlights the importance of driving manufacturers to publish EPDs for such products.

An analysis of the correlation between Global warming and other impact categories shows a risk of problem shifting towards other categories. Adding one more impact category, Mineral resource scarcity, increases the correlation to cover 16 of 18 LCIA categories. More research is needed to see if this finding is generalisable to other buildings.

4. Conclusions

The article documents the emissions for constructing the ZEB Laboratory in Trondheim, Norway, provided by the advisors' team, using the principle of lowering the carbon footprint systematically during the design and construction stages. Despite the design complexity, the assessment of the emissions for the materials and products applied in the building (stages A1–A3) shows a value of 4.0 kgCO_2-eq./m^2/year, which is the lowest compared to other ZEB projects in Norway. The result highlights the importance of emissions assessment since the predesign and execution stages to lower the carbon footprint.

Apart from the PV installations, the products with data confirmed from an EPD have 15% lower GWP values than the generic data. The difference is in range with the recommendations of the national emissions databases for construction in Nordic countries, which apply a conservative conversion factor of 1.2–1.25 when creating the generic database. This pattern is noted in the building's main material categories, such as wood, metal and concrete. In contrast, for layered products such as insulation or coverings, the emissions declared in the EPDs are higher than their equivalent from the ecoinvent database.

Although generic values are not as accurate as EPDs, they provide significant knowledge, particularly useful in the design phase. The preliminary generic results serve as the basis for assessing the carbon footprint of new constructions and initiating emission reduction measures. Through an increase in applications, systematic ratios can be useful for quick assessment and improvements during the design and construction of new buildings. When a generic intensity database of typical building materials and products is developed, it can be used by researchers and professionals for other construction projects, reducing time and calculation costs.

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CRediT authorship contribution statement

Arian Loli: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christofer Skaar:** Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Håvard Bergsdal:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Marte Reenaas:** Writing – review & editing, Validation, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110583.

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