IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: R Frischknecht *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012037

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012037 doi:10.1088/1755-1315/323/1/012037

Comparison of the environmental assessment of an identical office building with national methods

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Abstract. The IEA EBC Annex 72 focuses on the assessment of the primary energy demand, greenhouse gas emissions and environmental impacts of buildings during production, construction, use (including repair and replacement) and end of life (dismantling), i.e. during the entire life cycle of buildings. In one of its activities, reference buildings (size, materialisation, operational energy demand, etc.) were defined on which the existing national assessment methods are applied using national (if available) databases and (national/regional) approaches. The "be2226" office building in Lustenau, Austria was selected as one of the reference buildings. TU Graz established a BIM model and quantified the amount of building elements as well as construction materials required and the operational energy demand. The building assessment was carried out using the same material and energy demand but applying the LCA approach used in the different countries represented by the participating Annex experts. The results of these assessments are compared in view of identifying major discrepancies. Preliminary findings show that the greenhouse gas emissions per kg of building material differ up to a factor of two and more. Major differences in the building assessments are observed in the transports to the construction site (imports) and the construction activities as well as in the greenhouse gas emissions of the operational energy demand (electricity). The experts document their practical difficulties and how they overcame them. The results of this activity are used to better target harmonisation efforts.

1. Introduction
One major cause of greenhouse gas emissions (GHG), primary energy demand and environmental impacts is the construction of buildings and their operational energy demand for heating and cooling [1-4]. To support decision making in reducing environmental impacts, it is important to quantify the impacts and show opportunities for optimization. Environmental life cycle assessment (LCA) is commonly used to assess the environmental impacts of buildings during production, construction, use (including repair and replacement) and end of life. The LCA approach is standardized in ISO 14040 and 14044 [5, 6]. In addition, there are European standards (EN15978 [7] and EN15804 [8]) for the assessment of environmental performance of buildings and the development of environmental product declarations (EPD) of building products, respectively.

Today, there is disparity in the level of application of LCA on buildings and the existence of LCA databases targeted to the building sector across the world. The international research project IEA EBC Annex 72 focuses on the assessment of the primary energy demand, GHG emissions and environmental impacts of buildings occurring during production, construction, use and end of life. The main objectives of IEA EBC Annex 72 are among others to foster [9]:

- the discussion and harmonisation of methodology guidelines;
- the use of environmental information in an early design stage;
- the development and use of benchmarks;
- the development of national databases targeted to the construction sector.

To be able to establish harmonized methodology guidelines and identify areas of disagreement existing national methods are compared. Reference buildings are defined for that purpose on which the national LCA methods are applied. If available, national databases are used to quantify the primary energy demand, GHG emissions and environmental impacts.

2. Reference building
The "be2226" office building, located in Lustenau, Austria, is used as a reference building to evaluate existing national LCA methods. The building was designed by the architects Baumschlager Eberle architekten and built in 2013. It is a massive construction and can be seen as a low-tech building. The primary structure consists of pre-stressed and prefabricated concrete ceilings with overlay concrete and 76 cm thick exterior walls in composite masonry. The exterior walls consist of two layers of hollow perforated bricks, whereby the outer bricks are optimised for the insulating effect and the inner bricks bear the loads. The façades are covered on the outside as well as on the inside with lime plaster.

Due to its compact building shape, small and cleverly situated windows and thick exterior walls with a high thermal capacity, neither additional thermal insulation nor active heating and air-conditioning is required. The building is "heated" exclusively by the internal loads from devices and the lighting in combination with the heat dissipation of the people[27,28]. A Building Information Model (BIM) of the building was established by TU Graz. Based on this model the amount of building elements and materials required is quantified. The energy reference area of the building is 2421 m^2. All results shown in this paper are quantified against the energy reference area. The electricity demand for lighting and operating equipment is 196 MJ/m^2a.

3. Methods and databases

3.1. Used national methods including study period and databases

The assessment of the building was carried out by 22 different institutions using the same material and energy demand but applying different LCA approaches. Within the different approaches the primary energy demand, GHG emissions and environmental impacts were assessed. The focus in this paper is on the GHG emissions. In total 21 different national or regional LCA approaches were applied. The assessments of the be2226 building were carried out by the national experts, and results were reported in a uniform template that allowed for comparison between the countries. The applied methods are mainly used as part of a sustainability assessment and for certification schemes of buildings, design aid and in research activities in the respective countries.

The methods apply different reference study periods. 15 methods use a reference study period of 50 years for this case study[29]and six methods use 60 years. Denmark uses 80 years as reference study period (see Table 1). The reference study period has an influence on the relative importance of the GHG emissions of manufacture, construction, replacements and end of life stages on one hand, and the operational GHG emissions on the other. Furthermore, the methods differ in the used service life of building elements/components and the modelling of the end of life treatment of the materials. In cases the service life of a building element exceeds the reference study period, the reference study period is applied.

Table 1: Overview of the reference study periods and databases used within the LCA methods applied to assess the environmental impacts of the **"**be2226**"** building.

	Reference study period [years]	**Database**	**Field of application**
AT	50	ecoinvent 3.2[10]	Research
BE	60	ecoinvent 3.3 [11] adapted to Belgian context	Research and webtool (TOTEM)
BR	50	ecoinvent 3.4 [12] adapted to Brazilian context	Research
CA	60	ecoinvent 3.4 [12] adapted to Canadian context and EPDs	Building certification schemes, EPDs
CH, ETHZ	60	KBOB LCA data DQRv2 [13]	Building certification schemes
CH, HES-SO	60	KBOB LCA data DQRv2 [13]	Building certification schemes
CN	50	ecoinvent 3.5[14]; CLCD-China-ECER 0.8.1, Oekobau.dat [15, 16]	Building certification scheme
CZ	50	ecoinvent 3.3 [11], boundary condition from SBToolCZ methodology [17]	Decision-making tool, voluntary certification

[27] https://www.baumschlager-eberle.com/en/work/projects/translate-to-english-projekte-details/2226/ last visited on: 8.3.2019

[28] It could be argued that the internal loads from devices are a free heating source (waste heat) and that their electricity consumption shall not be attributed to the building's operational energy demand. However, for the purpose of this paper (comparing national assessment methods) electricity demand of devices is considered part of the operational energy demand.

[29] France is one of them, but usually uses 80 years.

	Reference study period [years]	**Database**	**Field of application**
DE	50	Ökobau.dat 2018 [16]	BNB
DK	80	Ökobau.dat 2016 [15]	DGNB Denmark
ES	50	ecoinvent 2.0 [18]	research
FR	No official requirement, 50 years in this case study, default value 80 years	ecoinvent 2.2 [19] adapted to French context	EQUER
HK	50	Studies and statistics [20-22]	Research
HU	50	ecoinvent 2.0 [18] adapted to Hungarian conditions wherever relevant (for products primarily produced in Hungary, adaptation of the electricity mix and natural gas)	Education and research
IT	50	Ecoinvent 3.4 [12], EPDs	Research
NL	50	National Environmental Database for building products (NMD 2.2) [23] - producer-specific data and generic LCA data from ecoinvent 3.3 [11].	Building permits
NO	60	Ecoinvent 3.3 [11], EPDs	Research, decision-making tool
NZ	60	NZ whole building whole of life framework - materials data developed from EPDs for materials and modelling in ecoinvent 3.1 [24] (specific process data with NZ Grid electricity)	Certification, research
PT	50	LCIA Database for Portuguese Building Technologies [25], based on generic data from Ecoinvent 2.1 [26], Ecoinvent version 3.3 [11]	Research
SE	50	Swedish Building Sector Environmental Calculation Tool (BM) [27]	Building certification schemes
UK	50	Database embedded in OneClickLCA[a]	Building certification schemes
US	50	Database embedded in ATHENA Impact Estimator[b]	Building certification schemes and research

[a] https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/, last visited on: 23.5.19
[b] https://calculatelca.com/software/impact-estimator/lca-database-reports/, last visited on: 24.5.2019

Mostly different versions of the ecoinvent database (i.e. [10-12, 14, 18, 19, 24, 26]) were used to assess the environmental impacts of the building. Some institutions applied country specific databases (see Table 1). The life cycle stages included in the respective approaches are shown in Table 2.

Table 2: Overview of the life cycle stages included in the applied approaches.

Life cycle stages	**A1-A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
AT	X	X					X		X	X		X	X	X	
BE	X	X	X		X		X	X	X	X	X	X	X	X	
BR	X	X	X				X		X	X	X	X			
CA	X	X	X				X		X	X	X	X	X	X	
CH, ETHZ	X						X		X		X	X	X	X	
CH, HES-SO	X						X		X		X	X	X	X	
CN	X						X		X					X	X
CZ	X						X		X						
DE	X						X		X				X	X	X
DK	X						X		X				X	X	
ES	X	X	X		X	X	X	X	X	X	X	X	X	X	
FR	X	X	X				X		X	X		X	X		X
HK	X	X	X	X	X	X	X	X	X		X	X	X	X	
HU	X	X	X			X	X		X			X	X	X	
IT	X					X	X	X	X	X					
NL	X	X	X		X	X	X	X	X		X	X	X	X	X

Life cycle stages	**A1-A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
NO	X						X		X				X	X	
NZ	X	X	X		X		X		X	X	X	X	X	X	X
PT	X								X	X					
SE	X	X	X												
UK	X	X	X				X	X	X		X	X	X	X	X
US	X	X	X		X		X		X		X	X	X	X	X

3.2. GHG emissions of construction materials

A preliminary contribution analysis of the different building elements to the total GHG emissions showed that bricks, concrete, windows and reinforcing steel are important. In Figure 1 the GHG emissions of brick along the life cycle stages (Modules A-D) as defined in EN 15804:2012 [8] are presented. Hong-Kong and the Netherlands did not report the emissions according to the life cycle stages. In all countries, which reported the emissions according to the life cycle stages, most of the GHG emissions of bricks are emitted in the product stage. While the GHG emissions in the product stage (A1-A3) of bricks are similar in all countries, differences are observed in the construction process stage (A4-A5). New Zealand reported a substantially higher impact in this life cycle stage than the other countries, mainly due to the large import distances of bricks from Australia to New Zealand (no domestic production). In the end of life stage (modules C1-C4) differences in the results are based on different assumptions on recycling shares, waste processing and final disposal scenarios. Germany reported negative GHG emissions in the end of life stage of bricks. According to the LCA data they use, the treatment in the decomposition phase leads to a complete carbonation of the free alkali- and alkaline earth oxides, which is accounted for as a credit. China assumed a high recycling potential for bricks and therefore reported high negative GHG emissions in the end of life stage. The highest GHG emissions of bricks are reported by Hong-Kong. Over all life cycle stages (i.e. without Module D) and excluding New Zealand and Hong-Kong the GHG emissions of bricks reported by the countries differ by a factor of 1.6.

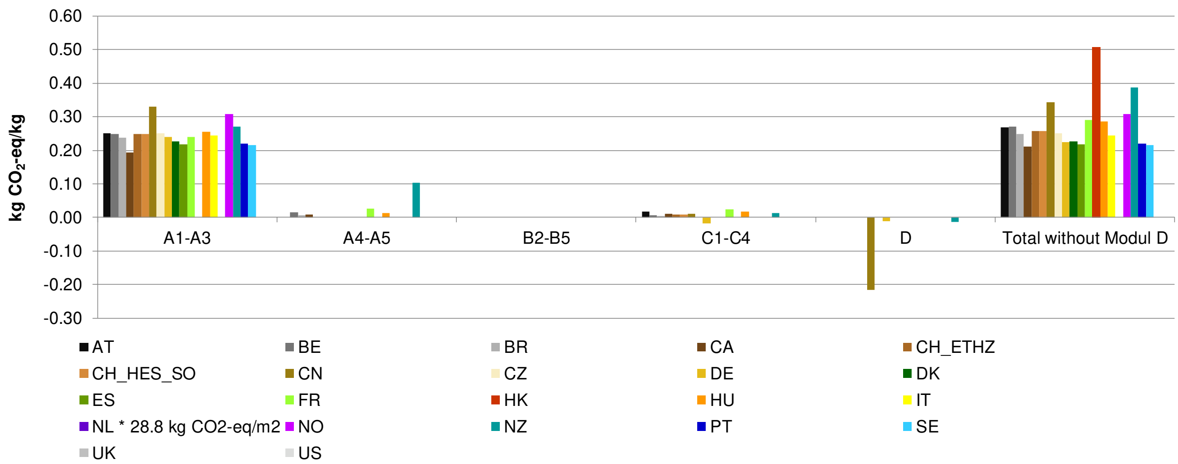

Figure 1. GHG emissions of bricks caused in the different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

In Figure 2, the GHG emissions in kg CO_2-eq/kg of concrete are presented. Most of the GHG emissions of concrete are emitted in the product stage. The emissions differ up to a factor of 2.2 between the countries. The main reasons are different energy mixes in clinker production (share of traditional and secondary fossil fuels such as hard coal, lignite, fuel oil and natural gas or used tires), different average shares of clinker in 1 kg cement and different cement contents in 1 m^3 concrete.

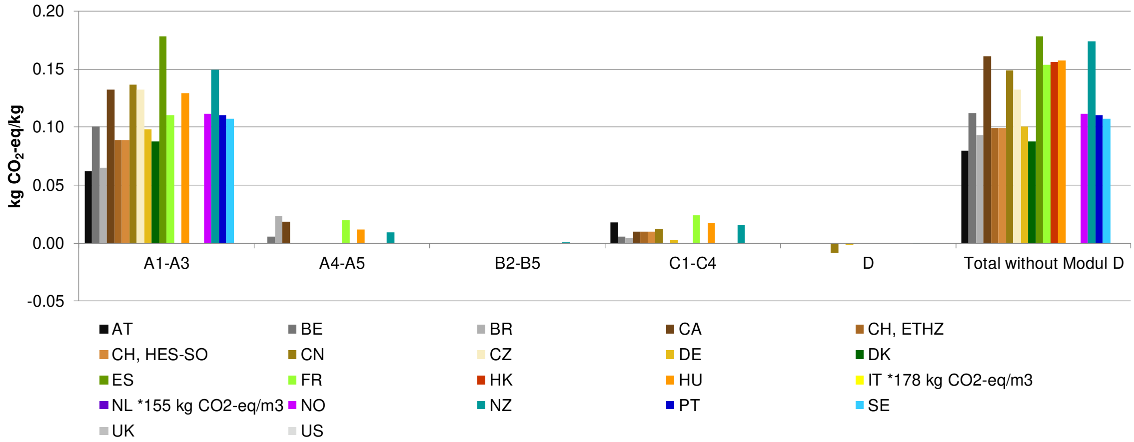

Figure 2. GHG emissions of concrete during different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

The GHG emissions in kg CO_2-eq/kg reinforcing steel are shown in Figure 3. In all country assessments the product stage of reinforcing steel contributes most to the GHG emissions. The highest reported emissions are around 6 times higher than the lowest ones. The main reason is the share of recycled content in the reinforcing steel. The approaches applied in China, France and New Zealand report the net benefits and loads beyond the system boundaries. In China the net benefit is 53 % of the total GHG emissions of reinforcing steel reported for A1-C4. In France, the net benefit amounts to 57 % of the A1-C4 emissions and in New Zealand 8 %.

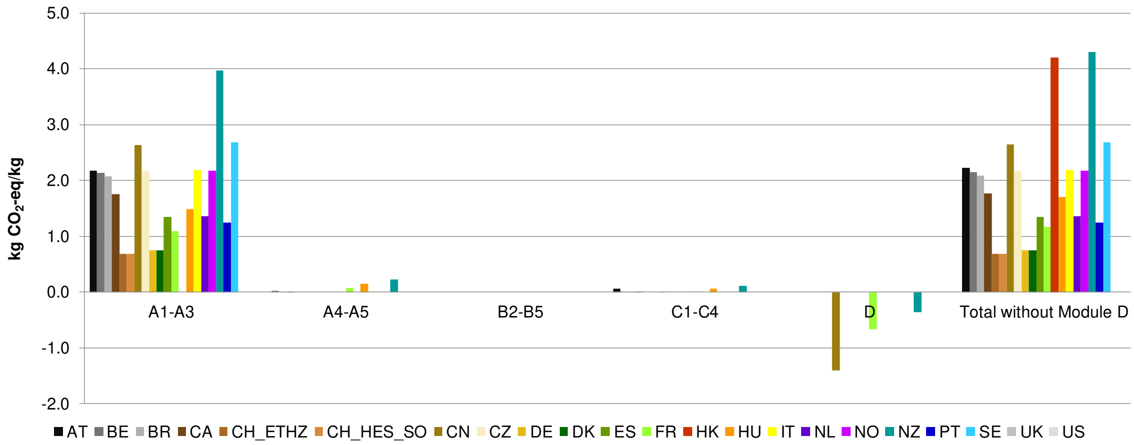

Figure 3. GHG emissions of reinforcing steel during different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

3.3. GHG emissions of electricity mixes

The GHG emissions of the electricity used in operation reported by the different countries differ substantially (see Figure 4). While Denmark, Norway and France report low GHG emissions of their electricity mix, China, Czech Republic, Hong-Kong, Hungary and the Netherlands report comparatively high GHG emissions. The highest reported emissions are 30 times higher than the lowest reported emissions. These differences in GHG emission from electricity reflect the real existing differences in the national electricity supply. Denmark is the only country reporting a future average mix based on renewable energies only.

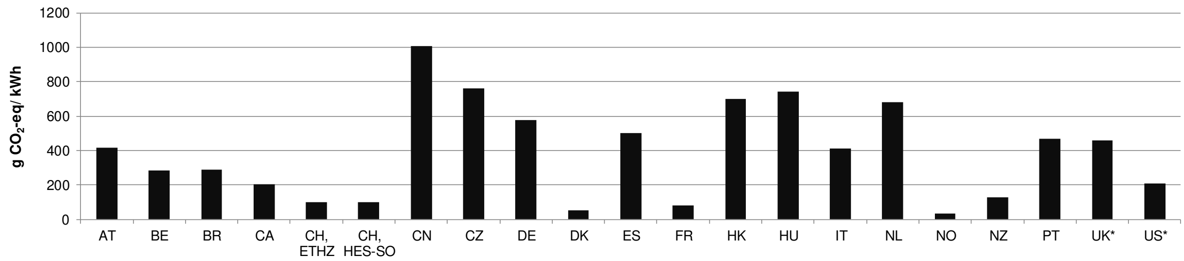

Figure 4. GHG emissions of the electricity mixes applied in the assessment of the operational electricity demand (module B6) of the reference building in g CO2-eq/kWh.
*: value back-calculated from the GHG emissions of B6

3.4. *Issues encountered during the assessment*

During the assessment of the reference building the authors of this paper encountered several issues with the provided data. Most of the issues were related to missing life cycle inventory data for specific materials, such as "vacuum insulation panels" and different aggregation stages in the information provided and the data available. The issue encountered with the aggregation level concerned the product level (e.g. reinforced concrete, instead of having separate LCI data on concrete and reinforcing steel) and the life cycle stages (e.g. data only available for the whole life cycle and not for Modules A, B and C separately). Furthermore, differences in the units of the building data and the available LCA data occurred (e.g. pieces vs. m^3 of stairs). To overcome the limitations of lacking LCI data for materials the authors used proxies, EPDs or did not consider the material and building elements at all (e.g. elevator).

4. Preliminary results: greenhouse gas emissions caused by the be2226 building

The preliminary results of the assessment of the GHG emissions caused by the manufacturing, construction, use and end of life of the reference building "be2226" are presented in Figure 5. The total GHG emissions reported are between 10 and 71 kg CO_2-eq/m^2a depending on the national approach used.

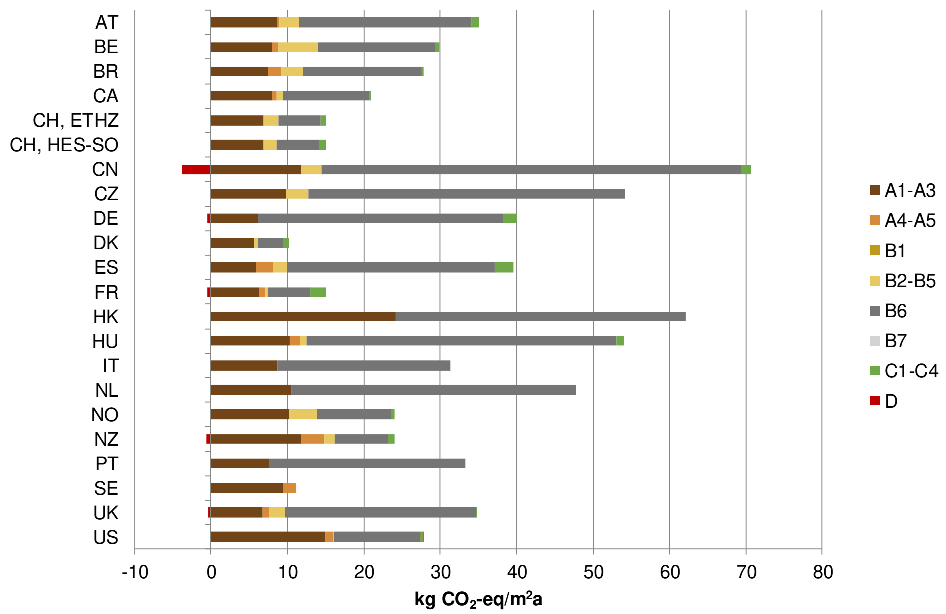

Figure 5. Greenhouse gas emissions in kg CO_2-eq per m^2 and year of the reference building **"be2226"** assessed according to the national/regional approaches of the countries listed (preliminary results).

Different life cycle stages were taken into account depending on the national approaches (see Table 2). Most of the countries were able to report the GHG emissions according to the life cycle stages defined in EN 15804:2012 [8] and EN 15978:2011 [7]. Hong-Kong and the Netherlands reported the emissions of modules A4, A5, B, C and D all together in the product stage (modules A1-A3) except the operational energy use (B6)[30]. The product stage was assessed by all countries and varies between 5.7 and 15 kg CO_2-eq/m^{2}a. Within the product stage the GHG emissions vary by a factor of 2.6 (excluding Hong-Kong). The transport to site and the construction and installation process (construction process stage A4 and A5) was addressed by 13 approaches. Over all countries those life cycle stages vary between 0.3 and 3.1 kg CO_2-eq/m^{2}a.

All national approaches, except Portugal and Sweden took the replacement (B4) of materials and building elements into account. However, only few approaches consider the maintenance (B2), repair (B3) and refurbishment (B5). Overall, the use stage (B2-B5) varies between 0.1 and 5.2 kg CO_2-eq/m^{2}a. A very high variability can be seen in the contribution of the operational energy use stage. It directly reflects the differences in GHG emissions of the electricity mixes (see Section 3.3) because electricity is the only energy carrier used in operation. The end of life stages (C1-C4) vary between 0.2 and 2.4 kg CO_2-eq/m^{2}a. This variation is not linked to the scope of end of life stage modules considered. Net benefits and loads beyond the system boundary were reported by six approaches out of 21. The approach applied in the Netherlands includes energy recovery from waste incineration and product reuse or recycling. However, the net benefits are not reported separately in the Dutch assessment. Where reported separately, the benefits are between 0.1 and 3.7 kg CO_2-eq/m^{2}a.

5. Discussion

In all assessments, most GHG emissions occurred either in the product stage or during the operational energy use. The differences in the operational energy use are due to the substantial difference in the GHG-intensity of the national electricity mixes. The variance of the GHG emissions occurring in the product stage is due to the different GHG emissions of the construction materials (see Section 3.2) and to the differences in the reference study period applied.

The Danish assessment shows the lowest GHG emissions per m^2 and year. Firstly, a reference study period of 80 years leads to lower annual emissions from the product stage (A1-A5) compared to the reference study period of 50 or 60 years. Secondly, the electricity mix applied during operation is a future national mix based on renewable energies with comparatively low GHG emissions per MJ.

The annual specific GHG emissions of this building are mainly influenced by the GHG intensity of the electricity mix used during operation. The GHG intensity of the construction materials used (Modules A1-A5) as well as the difference in reference study period cause additional differences in the annual specific GHG emissions of the "be2226" reference building. The contributions from the end of life stage are minor. The building hardly uses plastics and plastics-based insulation materials which would give rise for substantial GHG emissions when incinerated. On the building level, the potential loads and benefits beyond the system boundary are hardly visible.

The different applied approaches result in a wide range of the total GHG emissions of the "be2226" building. The differences in the results of the assessments of the "be2226" building are due to the substantially different CO_2-footprints of the energy carriers and the construction materials rather than methodological differences between the approaches applied. Hence, the relatively large differences are no cause for concern. Depending on the national context low carbon footprint buildings are achieved using different concepts. It is crucial however, that environmental benchmarks for buildings in a country are based on the LCA approaches and LCA databases used in that particular country.

[30] For reasons of confidentiality the Dutch National LCA database comprises only aggregated emissions data for the stages A, B, C and D together, in case of producer-specific LCA data.

6. Outlook

The comparison of all the national LCA approaches applied will be used to better target harmonization efforts and identify areas of disagreement. Furthermore, a second reference building, a Chinese high-rise building will be assessed by the IEA EBC Annex 72 participants to get a deeper understanding of the different approaches applied on a more complex building. The insights gained from both comparative exercises will be used along with other results of the international research project IEA EBC Annex 72 to develop and extend the methodology guideline on LCA of buildings and life cycle related environmental benchmarks.

Acknowledgments
The authors would like to thank the IEA for its organizational support and the colleagues involved in the project (Members: Australia, Austria, Belgium, Canada, Czech Republic, P.R. China, Denmark, Finland, France, Germany, Italy, R. Korea, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America, Observers: Brazil, Hungary, India, Slovenia) for their cooperation. Additionally, they would like to thank the organizations and institutions in the participating countries for their financial support.

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