Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches – IEA EBC Annex 72

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Abstract. **Introduction:** The international research project IEA EBC Annex 72 investigates the life cycle related environmental impacts caused by buildings. The project aims inter alia to harmonise LCA approaches on buildings. **Methods:** To identify major commonalities and discrepancies among national LCA approaches, reference buildings were defined to present and compare the national approaches. A residential high-rise building located in Tianjin, China, was selected as one of the reference buildings. The main construction elements are reinforced concrete shear walls, beams and floor slabs. The building has an energy reference area of 4566 m^2 and an operational heating energy demand of 250 MJ/m^2a. An expert team provided information on the quantities of building materials and elements required for the construction, established a BIM model and quantified the operational energy demand. **Results:** The greenhouse gas emissions and environmental impacts of the building were quantified using 17 country-specific national assessment methods and LCA databases. Comparisons of the results are shown on the level of building elements as well as the complete life cycle of the building. **Conclusions:** The results of these assessments show that the main differences lie in the LCA background data used, the scope of the assessment and the reference study period applied. Despite the variability in the greenhouse gas emissions determined with the 17 national methods, the individual results are relevant in the respective national context of the method, data, tool and benchmark used. It is important that environmental benchmarks correspond to the particular LCA approach and database of a country in which the benchmark is applied. Furthermore, the results imply to include building technologies as their contribution to the overall environmental impacts is not negligible. **Grant support:** The authors thank the IEA for its organizational support and the funding organizations in the participating countries for their financial support.

1. Introduction

The construction and operation of buildings are a major cause for climate change and other environmental impacts [1-3]. Environmental life cycle assessment (LCA) is widely used to quantify greenhouse gas (GHG) emissions and other environmental impacts of buildings and to highlight optimization and improvement potentials over their whole life cycle (production, construction, use - including repair and replacement - and end of life). LCA results support decision making in favour of a more climate and environmental friendly production and consumption and therefore help to achieve the UN Sustainable Development Goals (SDG) number 11 (sustainable cities and communities) number 12 (responsible consumption and production) and 13 (climate action).

The international research project IEA EBC Annex 72 investigates the life cycle related environmental impacts caused by buildings and aims inter alia to discuss and harmonise LCA approaches on buildings [4]. To present existing national approaches and identify commonalities and discrepancies three reference buildings were defined within the IEA EBC Annex 72 project. For each reference building an expert team provided the bill of materials and operational energy demands in local context. National experts assessed the environmental impacts using the provided information on quantities of building materials and operational energy demands, but applying their national or regional LCA approach and LCA database, whenever available.

The first analysed reference building was the “be2226” office building located in Austria. The building is a massive construction with thick exterior walls with a high thermal capacity. Therefore, no active heating and air-conditioning is required. 22 different institutions assessed the “be2226” office building according to their national or regional LCA approach and LCA database. Depending on the assessment the GHG emissions of the be2226 building were between 10 and 71 kg CO_2-eq per m^2 per year. Most of the GHG emissions were either caused in the product stage or during the operational energy use. The differences in GHG emissions were due to variances in GHG emissions per kg building material, differences in the applied reference study periods and the different GHG intensities of the national electricity mixes [5].

National or regional LCA databases reflect the production conditions and the energy mix in a specific country and are therefore important for assessing the environmental impacts in a true and fair view. Hence, it is no cause for a major concern if the environmental impacts of the same building differ between the different national approaches. However, it is recommended to use LCA databases representative for the countries' relevant economic sectors.

A residential high-rise building (TJ-CSY-11) located in Tianjin, China, was selected as one of three reference buildings within the IEA EBC Annex 72 project. Compared to the "be2226" office reference building [5], this residential building is more complex regarding materialisation and building technology. An expert team from the Tianjin University in China provided information on the quantities of building materials and elements required for the construction, established a BIM model and quantified the operational energy demand. The building has 12 floors and the main construction elements are reinforced concrete shear walls, beams and floor slabs. The building has an energy reference area of 4566 m^2. The operational energy demand is 250 MJ per m^2 per year. The operational energy demand includes space heating provided by a waste-heat-source heat pump operated with natural gas. The electricity demands for generating hot water, ventilation and cooling, elevators, lighting and other operational facilities were quantified separately.

2. Methods and databases

2.1. Used national methods including reference study period and databases

The environmental impacts of the high-rise building were assessed by 17 institutions. The authors of the study used the same material amounts and energy demand but applied their regional LCA methods for evaluating the primary energy demand (non-renewable and renewable) and the GHG emissions.

The LCA methods applied use different reference study periods, apply a different scope (i.e. life cycle stages included) and apply different background databases. 10 methods use a reference study period of 50 years and 4 methods use 60 years. New Zealand uses 90 years, France 100 years and Denmark 120 years as reference study period for the residential building. The ecoinvent database (different versions) was mostly used as background data source, but some country-specific databases (e.g. Ökobau.dat [6]) and EPDs were also applied (see **Table 1**).

A comparison of the environmental impacts of different materials and electricity mixes from different databases is presented in [5].

Table 1: Overview of the reference study periods and databases used within the LCA methods applied to assess the environmental impacts of the TJ-CSY-11 reference building.

	Reference study period [years]	**Database**	**Field of application**
AT	50	ecoinvent 3.5 [7]	Research
BR	50	ecoinvent 3.4 [8] /ecoinvent 3.5 [7] adapted to Brazilian context and EPD	Research
CA	60	ecoinvent 3.5 [7] adapted to Canadian context and EPDs	Building certification schemes, EPDs
CN	50	ecoinvent 3.5[7]; CLCD-China-ECER 0.8.1, Oekobau.dat [6, 9]	Building certification scheme
CZ	50	ecoinvent 3.3 [10], boundary condition from SBToolCZ methodology [11]	Decision-making tool, voluntary certification
DE	50	Ökobau.dat 2018 [6]	BNB and DGNB
DK	120	Ökobau.dat 2016 [9]	DGNB Denmark
ES	50	ecoinvent 2.0 [12]	research
FR	100	ecoinvent 2.2 [13]	EQUER
HU	50	ecoinvent 3.5 [7] adapted to Hungarian context	Education and research
IT	50	Ecoinvent 3.4 [8], EPDs	Research
NO	60	Ecoinvent 3.0 [14], EPDs	Research, decision-making tool
NZ	90	NZ whole building whole of life framework - materials data developed from EPDs for materials and modelling in ecoinvent 3.1 [15] (specific process data with NZ Grid electricity)	Certification, research

	Reference study period [years]	**Database**	**Field of application**
PT	50	LCIA Database for Portuguese Building Technologies [16], based on generic data from Ecoinvent 2.1 [17], Ecoinvent version 3.3 [10]	Research
SE	50	Swedish Building Sector Environmental Calculation Tool (BM) [18]	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: 8.01.2020
[b] https://calculatelca.com/software/impact-estimator/lca-database-reports/, last visited on: 8.01.2020

The life cycle stages included in the approaches are shown in **Table 2**. The life cycle stage B1 is not considered by any approach.

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

Life cycle stage	**A1-A3**	**A4-A5**	**B2**	**B3**	**B4**	**B5**	**B6-SH**	**B6-HW**	**B6-VC**	**B6-LO**	**B6-E**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
AT	X	X			X		X	X	X	X	X			X	X	X	
BR	X	X			X		X	X	X	X	X		X	X			
CA	X	X			X		X	X	X	X	X		X	X	X	X	
CN	X				X		X	X	X	X						X	X
CZ	X				X		X	X	X	X	X						
DE	X				X		X	X	X	X	X				X	X	(X)
DK	X				X		X	X	X	X	X				X	X	
ES	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
FR	X	X			X		X	X	X	X	X	X		X	X		X
HU	X	X		X	X		X	X	X	X	X			X	X	X	
IT	X						X	X	X	X	X						
NO	X				X		X	X	X	X	X				X	X	
NZ	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X
PT	X						X	X	X								
SE	X	X															
UK	X	X			X		X	X	X	X	X		X	X	X	X	X
US	X	X	X		X		X	X	X	X	X		X	X	X	X	

B6-SH: space heating
B6-HW: hot water
B6-VC: ventilation and cooling
B6-LO: lighting, operational facilities (electric doors, shadowing equipment), auxiliaries
B6-E: elevators

3. Results: GHG emissions of TJ-CSY-11 building

3.1. Results – life cycle stages

The national experts reported the results according to the life cycle stages defined in EN-15804:2012 [19] and EN-15978:2011 [20]. **Figure 1** presents the GHG emissions of the TJ-CSY-11 reference building over the different life cycle stages. Depending on the national approach used, the GHG emissions range between 15 and 67 kg CO_2-eq per m^2 per year.

The GHG emissions of the product stage were reported by all countries and differ between 4 and 16 kg CO_2-eq per m^2 per year. The construction process stages (A4 and A5) were assessed by 10 approaches and vary between 0.4 and 6.7 kg CO_2-eq per m^2 per year.

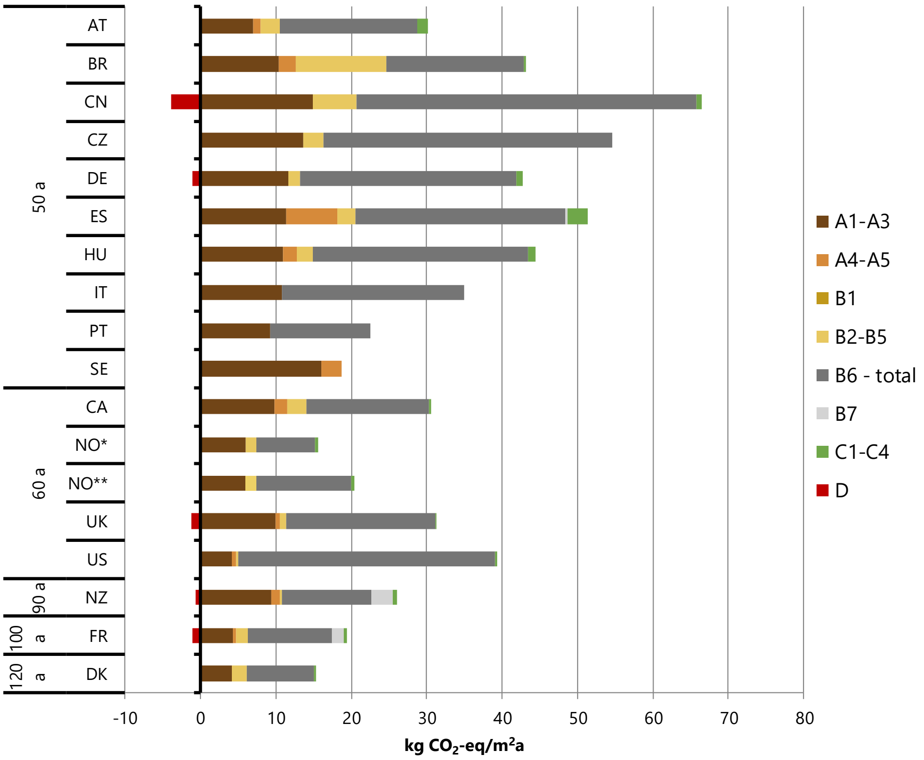

Figure 1. GHG emissions in kg CO_2-eq per m^2 per year of the reference building “TJ-CSY-11” assessed according to the national/regional approaches of the countries listed. Results variations reflect the different national methods and databases used. NO*: Norwegian electricity grid[1]; NO**: open electricity grid (EU 28+NO)[2]

The GHG emissions of replacements (B4) are between 0.3[3] and 11.9 kg CO_2-eq per m^2 per year, and were considered by all countries except Italy, Portugal and Sweden. The operational energy use (B6) was split into space heating, hot water, ventilation and cooling, lighting and operational facilities and elevators. 14 approaches considered all operational energy uses. China and Portugal did not consider the operational energy use from elevators. Furthermore Portugal did neither consider operational energy use from lighting and operational facilities. The approach applied by Sweden is not considering the operational energy use at all. Overall, the GHG emissions caused by the operational energy use vary between 7.9 and 45 kg CO_2-eq per m^2 per year. The difference is mainly due to the variations in the GHG emissions of the electricity mixes used in the different countries. The GHG emissions of the operational water use were assessed in 3 approaches and are of minor importance.

Different modules of the end-of-life stage were taken into account. The deconstruction stage (C1) was assessed by 6 countries, the transport to the disposal (C2) by 9 countries and waste processing (C3) and disposal (C4) each by 11 countries. The GHG emissions of the end-of-life stage are between 0.14 and 2.6 kg CO_2-eq per m^2 per year.

5 countries reported potential loads and benefits beyond the system boundaries (module D), which range between -3.9 and -0.6 kg CO_2-eq per m^2 per year.

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[1] Consideration of isolated energy system in Norway based on the dominant share of hydropower (based on the data from the Statistic Norway, www.ssb.no)

[2] Average value that is representative of a 60-year building lifetime, taking into consideration future evolutions in the European electricity generation towards 2050.

[3] New Zealand reported B4 together with B2.

3.2. Results – elements level

Figure 2 presents the GHG emission of the different building elements in the TJ-CSY-11 reference building (reported by 14 out of 17 countries) in kg CO_2-eq over the whole life cycle and reference study period. In 12 assessments most of the emissions caused by the building materials (i.e. without GHG emissions caused by operational energy use) are either caused by the interior walls or the exterior walls. In the Italian assessment the floor structure plus finishes and in the French assessment the building service systems cause most of the GHG emissions.

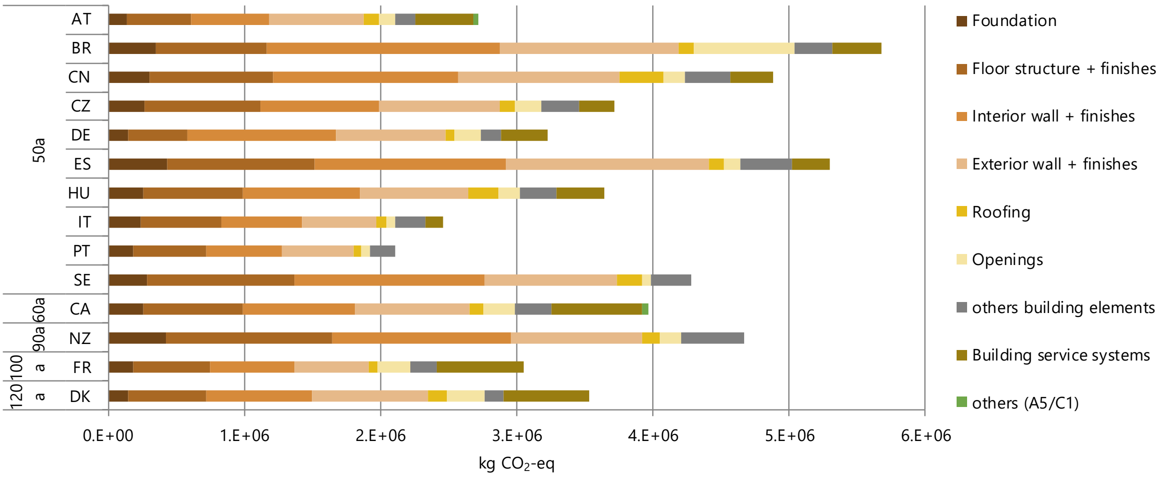

Figure 2: GHG emissions of building elements of TJ-CSY-11 in kg CO_2-eq over the whole life cycle and reference study period. Life cycle stages included, reference study period and applied databases differ between the national approaches.

The distribution of the shares of the GHG emissions of the foundation, floor structure, interior and exterior walls of the GHG emissions caused by the building elements is similar across the assessments from the different countries.

Within the approaches applying a 50 year reference period, the GHG emissions of the building elements vary between factor 2.5 and 3.4. Exceptions are the building element roofing and the openings, for which the GHG emissions vary by a factor of 6.1 and 11.8, respectively. An overview of the variance for each building element is shown in **Table 3**.

Table 3. Overview of the variance of the absolute GHG emissions of the building elements for the approaches applying a 50 years reference study period.

Building element	**Min GHG emissions [kg CO_2-eq]**	**Max GHG emissions [kg CO_2-eq]**	**Variation factor Max/Min**
Foundation	1.4E+05	4.3E+05	3.2
Floor structure + finishes	4.3E+05	1.1E+06	2.5
Interior wall + finishes	5.6E+05	1.7E+06	3.1
Exterior wall + finishes	5.3E+05	1.5E+06	2.8
Roofing	5.2E+04	3.2E+05	6.1
Openings	6.3E+04	7.4E+05	11.8
others building elements	1.5E+05	3.7E+05	2.5
Building service systems	1.3E+05	4.3E+05	3.4
Module D	-8.9E+05	-2.3E+05	0.3
others (A5/C1)	0.0E+00	3.6E+04	

The building service systems include the systems for water, sewage, electricity, heating, cooling, ventilation, elevator and hot water. The share of the GHG emissions of building service systems of the GHG emissions caused by the building elements is between 5 % and 21 % depending on the national approach applied. 3 countries out of 14 countries did not assess the GHG emissions caused by building service systems.

4. Discussion

In all assessments, except in the Swedish assessment, most of the GHG emissions are caused by the operational energy demand. In the Swedish approach the operational energy demand is not assessed. The differences in the GHG emissions of the operational energy demand are mainly caused by existing differences in the national electricity mixes.

As for the “be2226” reference building [5] the difference in the GHG emissions in the product stage are due to diversities in the reference study period applied and the differences in GHG emissions, caused by the production of the construction materials.

The GHG emissions caused by the production of materials used for the building service system tend to cause a more significant share of the total absolute GHG emissions with longer reference study periods. This is mainly due to the often shorter service life of the building service system compared to the building life time and thus leading to several replacements causing additional GHG emissions. For example in the Danish assessment the service life of the heating system is 30 years. A reference study period of 120 years leads to 3 replacements of the heating system. This effect is also observed for other building elements with a shorter service life (i.e. windows and doors), but they are of minor importance with respect to the total absolute GHG emissions of the building elements. However, the GHG emissions caused by the building service system of the assessments with a reference study period of 50 years show a similar variance like other building elements.

As in the “be2226” reference building case [5], the GHG emissions of the TJ-CSY-11 reference building differ substantially depending on the applied approach and are mainly due to the different GHG emissions of the energy carriers and construction materials used, differences in scope (inclusion or not of building service systems) and reference study period. In most cases, methodological differences are of minor importance. As concluded in [5], it is important that environmental benchmarks correspond to the particular LCA approach and database of a country in which the benchmark is applied.

Despite the variability in the GHG emissions determined with the 17 national methods, the individual results are relevant in their respective national contexts. Many nations run their labelling or certification systems applying a national method, national or nationally adapted LCA data and national building benchmarks. It is more important that a national assessment of the TJ-CSY-11 is in accordance with the national system of assessing environmental impacts of buildings than of reaching identical results in assessments done according to national approaches.

5. Outlook

A Canadian pre-fabricated wood building, will be the third reference building and assessed with a special focus on methodological choices of the modelling of biogenic carbon and biogenic CO_2 and CH_4 emissions. The lessons learned from the assessment of reference buildings by different national experts help to point out commonalities and discrepancies among the approaches applied. This knowledge is used along with other results to develop a harmonized methodological guideline for the assessment of GHG emissions and other environmental impacts in the full life cycle within the international research project IEA EBC Annex 72.

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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