IEA EBC Annex 57 ‘Evaluation of Embodied Energy and CO_{2eq} for Building Construction’

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KEY WORDS
Design process, Indicators, Embodied Energy, Embodied Greenhouse Gas Emissions, System boundaries, Life Cycle Assessment, Database.

HIGHLIGHTS

- Building-related embodied impacts are growing and should not be ignored.
- Ways of improving transparency in embodied impact assessments are proposed.
- Actor-specific guidelines can foster integration of embodied impacts into practice.
- The availability of quality-checked databases can support the entire process.
- A number of strategies for the reduction of embodied impacts are demonstrated.

ABBREVIATIONS

GHG	Greenhouse gas
EE	Embodied energy
EG	Embodied GHG emissions
EEG	Embodied energy and GHG emissions

ABSTRACT

The current regulations to reduce energy consumption and greenhouse gas emissions (GHG) from buildings have focused on operational energy consumption. Thus legislation excludes measurement and reduction of the embodied energy and embodied GHG emissions over the building life cycle. Embodied impacts are a significant and growing proportion and it is increasingly recognized that the focus on reducing operational energy consumption needs to be accompanied by a parallel focus on reducing embodied impacts. Over the last six years the Annex 57 has addressed this issue, with researchers from 15 countries working together to develop a detailed understanding of the multiple calculation methods and the interpretation of their results. Based on an analysis of 80 case studies, Annex 57 showed various inconsistencies in current methodological approaches, which inhibit comparisons of results and difficult development of robust reduction strategies. Reinterpreting the studies through an understanding of the methodological differences enabled the cases to be used to demonstrate a number of important strategies for the reduction of embodied impacts. Annex 57 has also produced clear recommendations for uniform definitions and templates which improve the description of system boundaries, completeness of inventory and quality of data, and consequently the transparency of embodied impact assessments.

1. Introduction

The conservation of energy and material resources, and the protection of the global climate, are key goals of sustainable development. Over 40 percent of global energy consumption and about 30 percent of global greenhouse gas (GHG) emissions can be contributed to the building sector (UNEP 2009, IPCC 2014). While regulations have reduced energy consumption in the operation of new buildings, the combined effects of an increasing population and high construction rates are nevertheless likely to see these contributions rise further in the future. It is clearly imperative that the current efforts to reduce GHG emissions from the building sector should be intensified.

The current regulations to reduce energy consumption, and thereby GHG emissions, from buildings have focused on the operational phase of the building (EPBD 2010, ASHRAE 2013). Calculations of operational impacts have become increasingly accurate, and have led to the design of highly energy efficient building envelopes and systems. One example of the effectiveness of this policy is demonstrated by Denmark, where the requirements for operational energy use in new buildings has reduced to less than one third over the last 25 years (EFKM 2014).

Importantly, however, legislation currently excludes measurement and reduction of the embodied energy and greenhouse gas emissions (EEG) of buildings. These are the impacts from manufacturing the construction materials, and constructing, maintaining, refurbishing and deconstructing the buildings, and are a significant and growing proportion; for example, 72% of the whole life GHG and 50% of the whole life energy over 80 years for a Danish office (Birgisdottir and Madsen, 2017), and 60% of whole life GHG and 33% of energy over 58 years for a UK school building (Gavotsis and Moncaster, 2014).

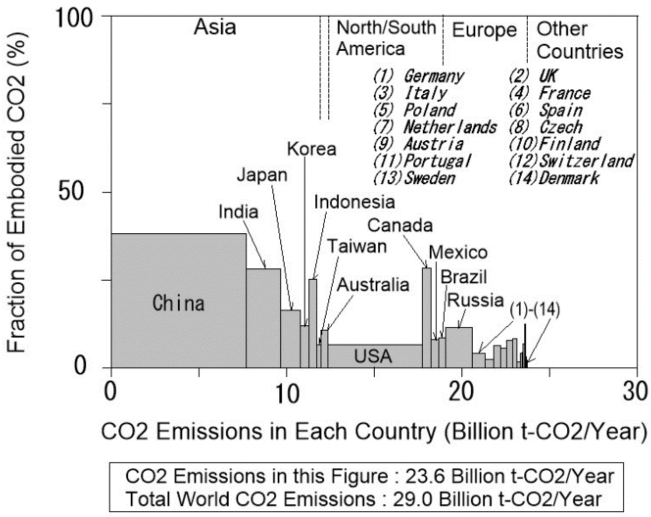

Figure 1. Total CO_2 emissions in each country and the fraction of embodied CO_2 (Yokoo, N. et al., 2015).

A macroeconomic analysis can identify the share of embodied impacts by country. An estimation of the total CO_2 emissions in various countries and the corresponding fractions of embodied CO_2 emissions due to building construction and public works are shown in Figure 1 as a result of analysis of world Input-output (IO) tables. The embodied energy and CO_2 emissions differ depending on the building design, the energy intensity of materials, the national energy mix and the quantity of materials used (Oka et al., 2016), but are clearly significant.

It is increasingly recognised therefore that the focus on reducing operational impacts needs to be accompanied by a parallel focus on reducing embodied impacts.

Methodological improvements have been made in recent years in developing and harmonising the life cycle assessment method for buildings, by International standards such as ISO

21929-1:2011, ISO 21931-1:2010 and the European standards developed by Technical Committee TC350, including EN 15643-2:2011 and EN 15978:2011. In these standards, environmental product declarations (EPD) of construction products, which utilize process based life cycle analysis methods, are seen as a source of information – see also ISO 21930:2007 and EN 15804:2012+A1:2013 (both currently under revision). Especially in Europe, the use of EPD's is well advanced. However, other areas of the world continue to apply alternative methods based on input-output and hybrid analyses (for example in Australia: Crawford, 2011, and in the US: Dixit, 2017), and there is considerable evidence to show that calculation approaches, methods, indicators and data continue to vary greatly (Säynäjoki et al, 2017, Anand and Amor, 2017, Rasmussen et al., 2017, Pomponi and Moncaster, 2016, Georges et al., 2015, Lützkendorf et al., 2015, Houlihan Wiberg et al., 2014). These authors and others make it clear that existing standards are not delivering enough harmonization in all of the approaches, and that more work is needed.

Over the last six years the International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) Annex 57 on 'Evaluation of Embodied Energy and CO_{2eq} for Building Construction' has addressed this issue, with researchers from 15 countries working together on this topic (Oka, 2016, Yokoo and Yokoyama, 2016). The two main research questions were: 'How should the continued limitations and variations in the assessment of embodied impacts of buildings be addressed and overcome?', and 'How should embodied impacts of buildings be reduced?'. To supplement these questions, other subsidiary questions were: 'How should EEG be better linked to protection goals and sustainability?', 'What are the trends since 1990 and what is the current state of the art in dealing with embodied impacts of buildings in the academic literature?' and 'What is the current state of practice in methodologies, and availability of data, for use in assessing embodied impacts of buildings?'.

The work within Annex 57 was therefore divided into four subtask groups, each with a specific objective related to each research question. These are covered in detail in the published reports of the subtasks (references in parentheses), and are described in this paper in the following order:

- Section 2 considers the scientific discussion through an evaluation of the available literature, based on the work of subtask 2 (Chae and Kim, 2016). It also summarises information on data and methodologies currently used in embodied impact assessments, based on the work of subtask 3 (Seo and Foliente, 2016).
- Section 3 describes the resultant recommendations for indicators and system boundaries and develops a unified description of the building, its life cycle and data needs, based on the work of subtask 1 (Lützkendorf and Balouktsi, 2016a).
- Section 4 describes how the analysis of 80 case studies was used to develop approaches for the policy, design and construction of buildings with low EEG, based on the work of subtask 4 (Birgisdottir et al., 2016).

Based on the reports of the subtasks, Annex 57 has also published a set of user-friendly guidelines for various stakeholders, including Design Professionals and Consultants, Policy Makers, Construction Product Manufacturers, and Educators, to support their individual decision-making processes (see Lützkendorf and Balouktsi, 2016b, Birgisdottir and Houlihan Wiberg, 2016, Passer et al., 2016, Mistretta and Guarion, 2016 and Železná et al., 2016). These guidelines are based on the work which is published in the subtask reports.

The purpose of this paper is to provide an overview of the work of the Annex 57. It outlines the main activities and findings of the project, and points interested readers towards the published subtask reports; there is not the space to describe the research of this project in detail, but we hope that interested readers will access the subtask reports and guidelines and the forthcoming papers addressing individual research outcomes.

2. Methods and data for embodied impacts of buildings

Subtasks 2 and 3 considered the research questions "What are the trends in the field of "embodied impacts" over the last decades?" and 'What is the current state of the art in the determination and assessment of embodied impacts of buildings in the academic literature'? An initial literature review was based on a search under the keywords "Embodied energy", "Embodied GHGs" and "Embodied CO_2" (EEG) through the website of ScienceDirect. Over 3,822 relevant books, journals and papers were identified between 1990 to 2013. As shown in Figure 2, the interest in EEG has been grown drastically since 2006. Approximately 250 of these publications were selected for in-depth analysis based on their relevance to the building and construction sector.

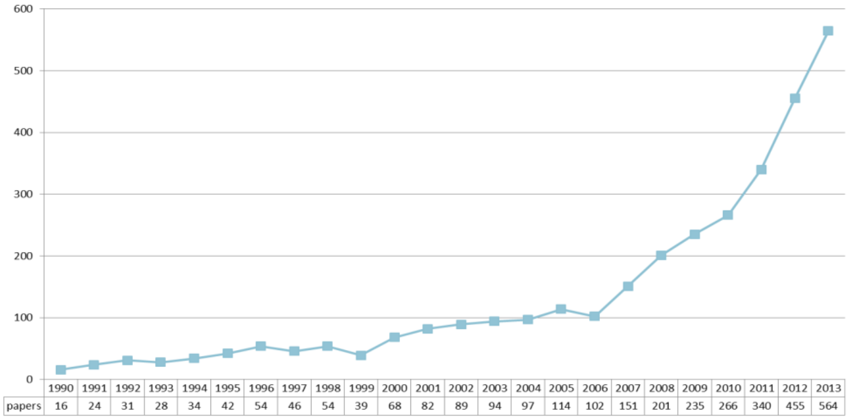

Figure 2. Number of published literature in embodied energy /GHGs study (Chae and Kim 2016).

2.1 LCA methodologies

The review of these publications showed that several variations of LCA methodologies have been applied to assess EEG. The choice of method for developing product data usually depends on the purpose and scope of the task, the required level of detail, the acceptable level of uncertainty, and available resources (data, time, human resources, know-how and budget).

Input-output (I-O) LCA, which uses sectoral monetary transactions data (national input output data) to account for the complex interdependencies of industries in modern economics, has been widely used to understand impacts at the national or global level (Tarancon, 2012). Meanwhile process-based LCA, collecting data for specific unit processes and linking them into larger processes to model the environmental impacts of product or system over its life cycle, has been applied increasingly frequently in order to understand environmental impacts at a building level

(Chae and Kim, 2016). However, I-O methods are also used at the building level and component level, especially in countries where there is insufficient process-based LCA data. A number of hybrids of the two methods have been proposed, which either start with an IO table and add process data for specific manufacturing processes, or start from a process based LCA and add inputs for which no process LCA data is available. Applications of all three LCA methods can be found at the material and construction product level (Seo and Foliente, 2016). Table 1 summarizes the key characteristics of the three main methods.

Table 1 Summary of different embodied impact calculation methods (Seo and Foliente, 2016).

Method	Process method	IO analysis	Hybrid analysis
Data input	• Company data • Associations data • Industrial data (statistics) • Public authorities data (e.g. road transport emissions and energy consumption), energy and environmental performance of power plants, waste incinerators etc.) • Scientific publications	• National statistics on annual sectorial production (physical and monetary), imports, exports, investments and consumption • National statistics or information on intersectorial purchases and delivery of intermediate products and services • National statistics on annual emissions and resource consumption, • Allocation of the national emissions and resource consumptions to the economic sectors.	• Process data • LCI data • Economic data • Economic input-output data
Data output	kg CO_{2eq}, MJ etc per product or building based	kg CO_{2eq}, MJ etc per monetary based ($)	kg CO_{2eq}, MJ etc per product or building based
Calculation approach	Matrix inversion or sequential accumulation	Economical input-output matrix inversion	Combined “Process” & “IO” methods

2.2 Databases and alternative sources of information

For the assessment of EEG of a building, the availability and accessibility of data for building materials and construction products is clearly important (Chae and Kim, 2016). This information should be reliable and comparable so as to allow for useful comparisons to be drawn between different products and materials. At present, not all data use consistent boundaries, and product specific data from manufacturers are often incompatible with the more generic product data (Chae and Kim, 2016 and EDP, 2014). Variations in system boundary settings, modelling approaches and background data considerably influence the outcomes (Chae and Kim, 2016).

The literature shows that field survey, in which data is gathered by assessing energy related parameters directly from processes of factories or building sites, is the most common method used at every level of building parts (Figure 3).

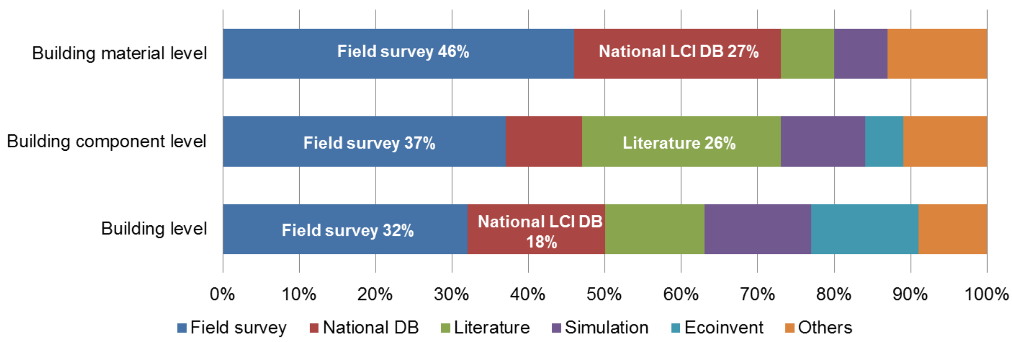

Figure 3. Common LCI database source in different level of building parts (Chae and Kim, 2016).

Other potential data sources include the academic literature, simulation, and LCI databases including commercial databases such as EcoInvent. Analysis of the literature however shows that transparency and traceability of data is sometimes lacking. Researchers also use different terms and definitions (for example, "embodied energy" is referred to as "grey energy" in the Swiss context (SIA, 2010)), and have set different system boundaries, research study periods, and calculation parameters, depending on their study purpose and the chosen methodology (Crishna, 2011).

It is therefore more advisable to use available databases and additional LCAs subject to a quality control. Where a new database is being developed or an existing one added to, for both process and I-O methods, Seo and Foliente (2016) propose that it should adhere to least six minimum requirements shown as Table 2.

Table 2. Minimum requirements for EEG-database for construction products (Seo and Foliente, 2016).

Item	Description
Materiality	Should cover the most significant construction materials and building technologies
Consistency	Analysis of all construction materials follows the same modeling principles, apply the same system boundaries.
Transparency	This transparency enables the user to independently check the data quality of the underlying data.
Timeliness	The age of a dataset provided in a database is determining its quality.
Reliability	The data used to establish a dataset sourced from reliable information sources.
Quality control	Datasets offered in a database should undergo an independent and external verification or critical review.

Where such information is not available, specific field studies following the international standards should be used.

3. Proposals by Annex 57: Basic approach and definitions of EEG

In response to the problems identified and issues raised in the previous part, this section briefly discusses the methodological bases for the determination, assessment and presentation of EEG, as well as bringing forward proposals for their harmonization. It therefore offers the first part of the response to the question 'How should the continued limitations and variations in the assessment of embodied impacts of buildings be addressed and overcome?', and also addresses the question: 'How should EEG be better linked to protection goals and sustainability?'

3.1 Terms and Definitions

A broad diversity of terms on the one hand, and the uncertainty about how to interpret these terms on the other hand, are identifiable in the relevant literature (Dixit et al., 2012, Dixit et al., 2013, Langston and Langston, 2008).

Annex 57 has focused on two particular criteria within the environmental performance assessment of construction works: the consumption of primary (non-renewable) energy resources and the amount of GHG emissions caused by buildings, during their production and construction, and their maintenance and end-of-life.

The conservation of resources and the reduction of adverse effects on the climate are also two essential protection goals (SETAC, 1993), part of the current sustainable development goals (SDG's) (UN, 2017) and part of the environmental dimension of sustainable development. Protection goals can be considered a suitable basis for the development of assessment criteria for buildings and constructed assets.

To improve transparency, Annex 57 has proposed a consistent terminology for the quantification of embodied energy (EE) and embodied GHG emissions (EG), as shown in Table 3.

The indicators PE_f and PE_{nr} are derived from considerations related to resource depletion, and thus the environmental targets covered here are the “protection of fossil energy resources” and the “protection of non-renewable energy resources”. These are the two main indicators identified within Annex 57, covering the practical applications across the world – representing the supply side. The indicator PE_t is derived from considerations related to the total primary energy demand of a building – here as a partial term for production, construction, repair and replacement and end of life. However, primary energy resources can often serve two different purposes; their consumption can be both energy-related and non-energy-related. The latter case, known as feedstock energy, is the primary energy (resources) which is not consumed as a fuel, but used as a raw material. This applies to specific products embodying fossil materials without using them as a fuel, e.g. petrochemicals may be used as feedstock to make plastics and rubber, or biomass may be used as feedstock to make timber products. Currently one of the least stated parameters by most of the existing studies (Dixit et al., 2010), feedstock energy should be included in all cases from the theoretical point of view, and should always be reported separately as an additional indicator (a distinction between renewable and non-renewable feedstock is necessary). The related ISO/TC 59/SC 17 SC and CEN TC 350 standards do not use the term "feedstock energy", but do include indicators to describe these two cases (energy and non-energy related) of resource use, as shown in table 3.

Table 3 Different core and additional indicators recommended by Annex 57 in comparison to existing standards(Lützkendorf and Balouktsi, 2016b).

ASPECT	LIST OF INDICATORS (Annex 57)	ISO 21931-1 (2010)	EN 15978 (2011)
EE (MJ)	**CORE** – Consumption of primary energy fossil [PE_f]	Not included in this version (ADP _fossil to be included in the revised version)	Abiotic depletion potential (ADP_fossil fuels) for fossil resources
	CORE – Consumption of primary energy non-renewable (fossil plus nuclear energy sources) [PE_{nr}]	Use of non-renewable primary energy resources	Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials
	CORE – Consumption of primary energy total (renewable + non-renewable) [PE_t]	Two indicators are added up: * Use of non-renewable primary energy resources * Use of renewable primary energy resources	Two indicators are added up: * Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials * Use of renewable primary energy excluding renewable primary energy resources used as raw materials
	ADD – Consumption of fossil fuels as feedstock	Use of non-renewable material resources	Use of non-renewable primary energy resources used as raw materials
	ADD – Consumption of biomass as feedstock	Use of renewable material resources	Use of renewable primary energy resources used as raw materials
EG ($kgCO_2eq.$)	**CORE** – Global Warming Potential [GWP 100]	Global Warming Potential, GWP	Global Warming Potential, GWP
	ADD – F-gases as identified	It is not identified as a	It is not identified as a

	in Montreal Protocol	separate indicator	separate indicator
	ADD – Stored Carbon	It is not identified as a separate indicator in this version (but to be included in the revised version)	It is not identified as a separate indicator

The indicator GWP 100 is defined according to the most recent IPCC report (IPCC, 2014). In all cases, process emissions which result from specific chemical effects, e.g. CO_2 emitted as a chemical reaction in cement manufacture, are also included. If stored carbon is calculated, it should be reported separately as an additional indicator. In terms of the F-gases emitted due to use of specific insulation materials (e.g. XPS and SPF) and refrigerators or A/C equipment, although their release occurs during the use phase, decisions are taken during the construction phase. So far, there is no clear guidance on whether these emissions should be included within embodied or operational impacts. Annex 57 recommends that F-gases due to the use of specific insulation materials or specific equipment are reported as a separate indicator within embodied impacts, as shown in table 3.

In comparison with the current standards, Annex 57:

- describes selected individual aspects in more detail
- establishes closer ties with protection goals
- introduces the PEt indicator to describe the total demand for energy
- identifies stored carbon as a separate indicator, and
- deals with process-related emissions in a more transparent way.

It should be noted that different sources of energy can be included in the indicators quantifying embodied energy, and that different GHG emissions can be included in the $kgCO_2eq$.

A clear statement is needed in order to determine the exact character and scope of each indicator and allow comparisons between data, described further in Lützkendorf and Balouktsi, (2016a).

3.2 System boundaries

Clear definition of the temporal and physical system boundaries is important to ensure transparency and comparability. The international and European standards, ISO 14025:2006 and EN 15804:2012 for construction products and ISO 21931-1:2010 and EN 15978:2011 for building structures describe the life cycle of construction products and structures. Annex 57 complements these standards by providing working aids to facilitate documentation and improve transparency for the multiple stakeholders involved in the process.

For the temporal system boundaries, Annex 57 proposes a range from "cradle to gate" to "cradle to grave" plus the benefits and loads beyond the system boundary (Figure 4). While recommending that embodied impacts from all life cycle stages ("cradle to grave") should be considered for building-level EEG analyses where possible, Annex 57 suggests the system boundary "cradle to handover" is the minimum information required for a building. This establishes a minimum reporting requirement at the building level, just as "cradle to gate" impacts have become mandatory for construction products, and also allows for meaningful comparisons with construction costs.

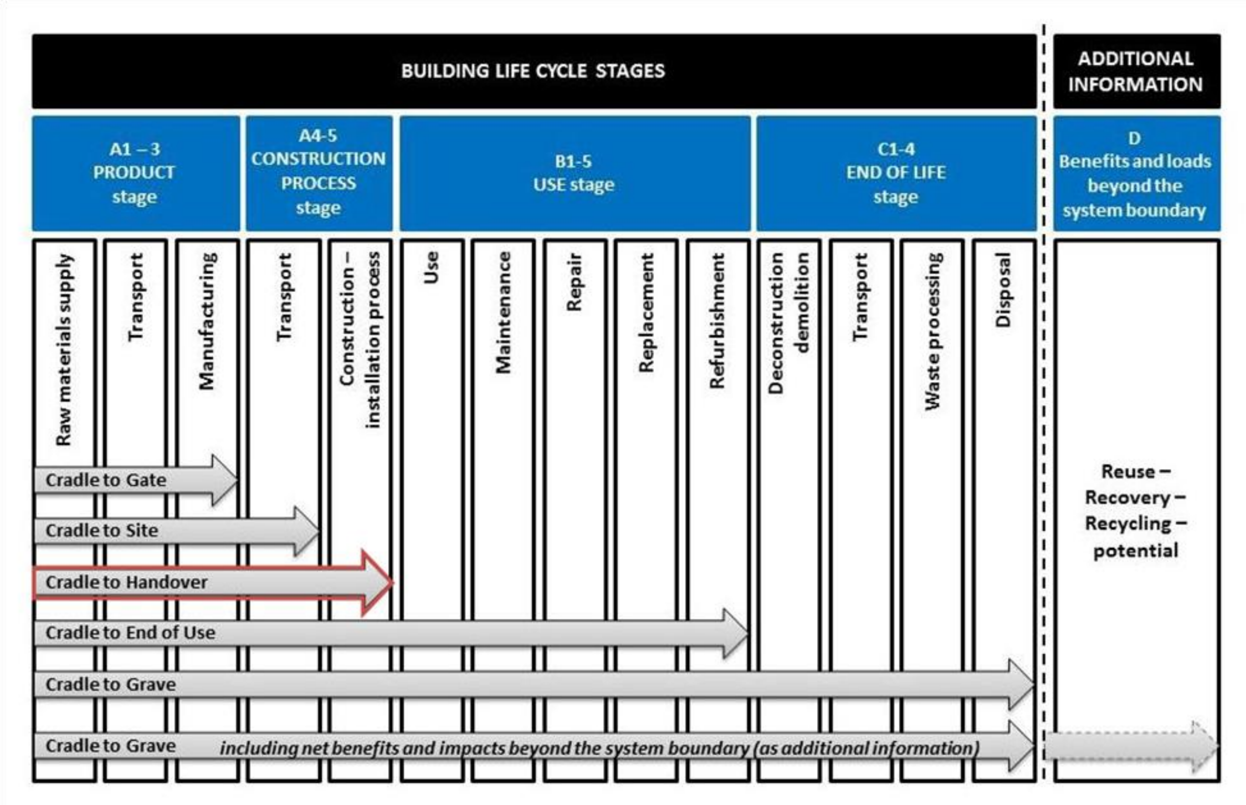

Figure 4. Proposed model for system boundary description and selection (modular structure adapted by EN 15978:2011) (Lützkendorf and Balouktsi, 2016a).

The physical system boundaries, meaning which parts of the physical building are included in the assessment, also need to be specified and reported clearly; Lützkendorf and Balouktsi (2016a) propose a clear checklist approach.

For the maximum possibility of reduction, EEG considerations need to be considered at the earliest design stages. One method is the inclusion of a "budget" for EEG as a project objective in the client's brief. Where suitable databases are available, designers should be able to link material quantities with the related EEG data, overcoming the obstacle of designers carrying out a complete life cycle assessment.

This section has addressed inconsistencies in the description of the indicators and the system boundaries of the assessment, and has considered practical approaches to the inclusion of embodied impacts in the decision-making processes related to building design. Appropriate construction product data is also required, and the provision and calculation of such data from a "data supplier" perspective are considered in the following section.

4. Case studies results and measures to reduce EEG on building level

The final task was to develop an understanding of the methodological choices and design strategies to reduce EEG emissions in building design and construction, in response to the question 'How should embodied impacts of buildings be reduced?'. It should be noted that of course embodied impacts are just one aspect of a multi-criteria decision-making process.

Over 80 building case studies were collected from within the Annex 57 group, and collated into a specially prepared template format, as a method for reporting dissimilar case studies with increased transparency, and for documenting the minimum data requirements proposed by Annex 57. The template included information on the building or project, length of reference study period, life cycle stages included, and database used. Sequential levels of analyses were then applied; the first analysed the impacts of methodology; the second used this understanding to interpret the relative impacts of different life cycle stages, components and building typologies; and the third built further on this to identify the potential design and construction strategies for reducing EEG (Birgisdottir et al., 2016, Birgisdottir, 2016). These are described in the sub-sections below. A fourth, qualitative, analysis on the impact of context on decisions, is included in the subtask report and in future publications but not covered further in this paper.

4.1 Impact of methodology on numerical results

A number of different methodological choices were identified within the collected case studies. Firstly there was a large variation in which life cycle stages were included in the different case studies. The majority include results for the production ((A1-A3: 98%) and replacement modules (B4: 71%). Just over half included waste processing and disposal (C3-C4: 55-61%) and reuse, recycling and disposal modules (D: 44%). Around one forth included the construction process stage (A4-A5: 23-26%), one fifth of the case studies included deconstruction, demolition and transport modules (C1-C2: 19-20%) and finally, a small percentage dealt with use and maintenance modules (B1-B2: 1-10%). This correlates well with the review carried out by Pomponi and Moncaster (2016).

Focusing just on the cradle-to-gate (A1-A3) embodied GHG emissions in a selection of the Annex 57 case studies, figure 5 demonstrates the high variability in numerical results; in fact there is a factor of almost 100 between, -6.8 to 637 kg CO_2/m^2. A detailed comparative analysis of these studies shows that the deviation in results is in part due to other methodological factors. One example is the purpose of study and the subsequent level of detail of the data used. The Norwegian case study (NO1) and the Swedish cases (SE2b and SE4) are based on the early design stage with correspondingly lower level of details. By contrast, another Norwegian case study of a comparable building (NO4) is an “as built” case study based on a highly detailed inventory. It can be seen that the EG is twice as high for the “as built” case compared to the early design case. A second example of methodological choice is that of functional equivalent, such as the specification of the area of the building. For example the heated floor area in the Norwegian cases is measured to the inside of the external walls while in Denmark it is measured to the outside of the external walls.

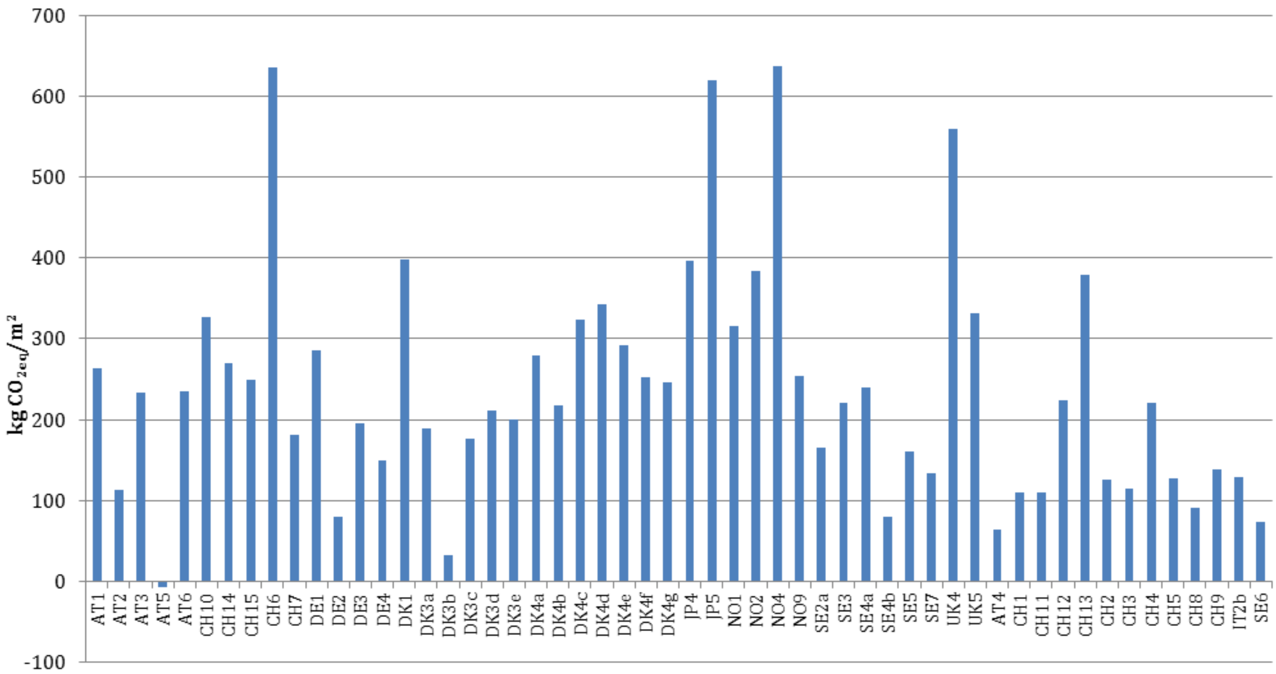

Figure 5. Cradle-to-gate (A1-A3) EG from available Annex 57 case studies in kg CO_{2eq}/m^2. (Birgisdottir et al., 2016).

There are many other methodological differences, including the LCA method used, the system boundaries, the assumed future scenarios for service life of materials and end-of-life treatments, the reference study period, and the source of data. These differences and their effects on the outcomes are explained in more detail in Birgisdottir et al. (2016) and Rasmussen et al. (2017). The variations in the methodologies used in these recent case studies illustrate that, despite the development of International and European standards (ISO 219310-1:2010 and EN 15978:2012), there remain multiple methodological approaches, and there is still a need for further guidelines and for the transparent and comprehensive declaration of methodological choices.

4.2 Relative EEG due to different life cycle stages and different components

The second analysis considered the relative contributions to EEG from different life cycle stages, building elements and different materials. As shown in figure 6, some generally accepted trends were supported by this analysis, including the dominance of the production stage (modules A1-A3) as a proportion of whole life EG for new buildings. However in some cases the replacement and refurbishment module (B4-B5) was within the same range as shown in Fig 6.

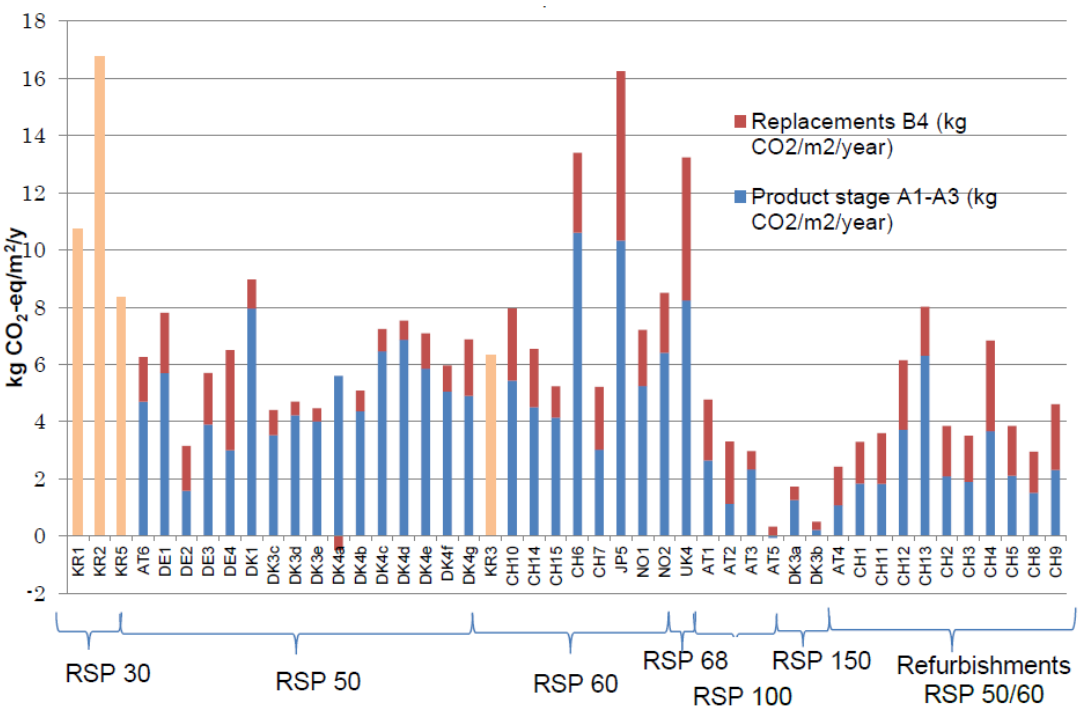

Figure 6. Cradle-to-gate (A1-A3) + replacement (B4) EG from available Annex 57 case studies. Orange bars

indicate case studies where reported results are a sum of production and replacement impacts.

Where they were included in the assessment, and in particular where the replacement stage was calculated, services components such as heating and ventilation systems and PV were found to be responsible for a high proportion of the whole life EEG. In the German case studies (DE1-DE4) technical equipment accounts for 18-46% of the life cycle EG in a building and 12-30% of EE. In all the Norwegian case studies (NO1-4), the PV was consistently found to be responsible for 30% of the EEG, and for high replacement emissions due to a relatively short lifetime of 20 years. Birgisdottir and Rasmussen (2016) suggest that the contribution of such components will become higher with the increased focus on self-sufficient energy buildings, in which EE of services components count for 40% of the total life cycle EE. However these components are currently frequently excluded from assessments, often due to lack of data (Passer et al., 2012).

4.3 Strategies for the reduction of EEG in buildings

The third analysis builds upon the insights gained from the analyses above, in order to develop EEG reduction strategies. Three overarching strategies have been identified and include; substitution of materials, reduction of resource use, and reduction of construction and end-of-life stage impacts.

For the first category, a number of case studies demonstrate that substitution with bio-based materials will reduce EEG due to the low-energy production methods (Nakao et al., 2011, Brown., 2013, Wallhagen et al., 2011, Monahan and Powell., 2011, Vukotic et al., 2011, Darby et al., 2013). Substitution of timber in large building components has a relatively high potential to reduce embodied greenhouse gas emissions. However, there are large variations in reduction from 27-77% depending on the building design (Birgisdottir et al., 2016).

Substitution using recycled materials (which have undergone reprocessing or renewal) and reused components (with minimal treatment) was also considered in several case studies. This showed a clear, and sometimes large, potential for reduced EEG. A UK case study looking into the use of cement substitutes and recycled aggregate in concrete for the Olympic stadium showed 12% reduction through cement substitution (Henson, 2011). A Danish case study on a residential building showed EEG reductions of 75-80% through the widescale use of recycled and reused components (Rasmussen and Birgisdottir, 2013). However ambiguities still exist in the calculation methodologies regarding impact allocation for the recycled and reused materials.

Within the second strategy, reduction of resource use, the reduction of virgin material use though the use of light-weight construction, or through the recycling and reuse of materials and structures, are both shown to be effective approaches (e.g. De Castro et al., 2014, Dokka et al., 2013, Kristjansdottir et al., 2013; Inman and Houlihan Wiberg, 2016). Service life extension, where coupled with the use of more durable components, is also shown to decrease EEG (e.g. Rauf and Crawford, 2015, Rasmussen and Birgisdottir, 2013, Yokoyama et al., 2015). Only limited studies exist which examine the impact of strategies such as design for flexibility, adaptability and reuse (e.g. Knight, 2013, Rasmussen and Birgisdottir, 2013). One is a Danish residential case study building which integrates the external wall elements so that they can be easily reused if extending the living area of the house, and has an internal wall system which can easily be moved to change the lay-out of rooms. These strategies can half the replacement EEG emissions in module B5 (Rasmussen and Birgisdottir, 2013).

Finally, while the construction module (A5) and the end of life stage modules (C1-C4 and D were found to contribute a small share of the total EEG, the type of energy-carrier, energy efficiency on site, site waste management, and seasonal timing of construction work, were shown to have the potential to reduce EEG (e.g. Liljenström et al; 2015).

5. Summary and conclusions

An intensive focus on lowering the operational energy consumption in buildings during the past decades has had a marked and widespread effect. From 2020 there will be a requirement for all new buildings to have “nearly-zero energy” in operation in Europe (EPBD, 2010, ASHRAE, 2013). Embodied impacts (EEG) can already equal 50-70% of the total impacts of a building’s life cycle over 80 years (Birgisdottir and Madsen, 2017), and this will grow both proportionally and in real terms with the reduction of operational impacts. Embodied impacts can therefore no longer be ignored as part of the overall performance and environmental sustainability of construction works and their consideration and calculation should become the norm worldwide. There are already standards for the determination and assessment of the environmental performance of buildings that include embodied impacts, but they do not always define and present the related system boundaries and indicators in a practice-oriented way, leaving a broad room for interpretation. The collection of 80 case studies from multiple countries by Annex 57 revealed the extent and number of methodological differences that can arise, and clearly demonstrated the need for basic principles, data and planning recommendations in order to ensure that EEG assessments are transparent and traceable. The Annex 57 results contribute towards addressing the limitations and variations identified, and creating a common understanding among practitioners around the world. Three particular results that can provide a basis and stimulus for the development of the current revisions of ISO 21931-1:2010 and EN 15643-2:2011 include: the recognition of the time of completion of the building as an important temporal system boundary; the clarification that feedstock energy and biogenic carbon shall be treated and communicated as additional information; and the allowance of flexibility in the selection of system boundaries while setting, at the same time, clear rules for documentation to improve and ensure transparency. It can be argued that the existing standards do not speak the "language" of practitioners and should be complemented by guidelines. The actor-specific guidelines of Annex 57 are first proposals to this end, which can be further developed into technical specifications (ISO TS). In particular, the various templates designed by Annex 57 for the description of indicators, checking the completeness of the building and its lifecycle model, as well as the declaration of boundary conditions for case studies, will form a useful basis for this purpose. Against the background of existing data gaps, it is currently not necessary to define uniform requirements and structures for databases. Rather, the transparency of current databases has first to be improved. Whether and which specific standards have been used as a basis for their development should be clearly indicated. In the medium term, in the field of data generation, a stronger orientation towards ISO 21930 (a new version of 2017 is currently available) and EN 15804 (currently under revision) can be recommended.

Reinterpreting the large set of case studies through an understanding of the influence of the different methodologies has also enabled the demonstration of a number of important strategies for the reduction of embodied impacts.

6. Further research and follow-on activities

During the course of the research, a number of questions arose, and the authors suggest the following questions for further study in the embodied impacts of buildings:

- How can the effects of the durability/ longevity of buildings be better taken into account? And, what is the appropriate reference study period for each building type and type of use?
- How can the construction product industry be motivated to close the existing data gaps, particularly in the field of building services and equipment?
- How should future technological advances in efficiency, and future changes in the electricity grid, be accounted for in replacement of products?
- What are the possibilities for new calculation methods and models (BIM) to lead to a

greater consideration of embodied impacts in the design process?

One possibility for dealing with these questions is provided by the new international project IEA EBC Annex 72 “Assessment of cycle-related environmental impacts caused by buildings”, beginning at the end of 2017 and running until 2022,

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