Design and construction strategies for reducing embodied impacts from buildings – Case study analysis

1 Introduction

The reduction of the operational energy demand and associated greenhouse gas (GHG) emissions in buildings is of high priority for the European Commission [1], primarily through the successive recasting of the Energy Performance of Buildings Directive (EBPD) 2012/27/EU [2] and the related national building regulations. However, apart from their operational energy use, buildings also consume primary fossil fuel energy during other phases, such as 'cradle' to construction, maintenance, replacements and demolition to waste processing phases. This embodied energy, together with the operational energy, constitutes the total primary energy or life cycle energy of buildings. An increasing number of academic studies now point towards the decreasing proportional impact from operational energy (and GHG emissions) as a result of reducing final energy demand and replacing primary fossil fuels by renewables [3], [4], [5], [6], [7], [8]. From being a topic hardly considered in building regulations to date, policy-makers and stakeholders in the construction industry are now showing a growing interest in the possibilities for reducing embodied energy (EE), and embodied GHG emissions (EG) [9], [10], [11]. A couple of recent initiatives by national authorities have, however, investigated [12], [13], [14] or even implemented the inclusion of embodied energy and greenhouse gases (EEG) in the building regulations [15]. This growing interest is also reflected by the dramatic increase of academic papers published on the topic during the last couple of years [16].

Given the growing importance of EEG, the Energy in Buildings and Communities Programme (EBC) of the International Energy Agency (IEA) agreed on implementing the project 'Annex 57 -Evaluation of Embodied Energy and Carbon Dioxide Emissions for Building Construction'. Sub-task 4 of this Annex developed a compilation and conducted an analysis of a large number of international case studies. This paper describes some of the results from this sub-task, namely, the analysis of design and construction strategies for reducing EEG in buildings. Even though professional and environmentally concerned stakeholders have for a long time had general rules of thumb for environmental design, only a limited number of cases have existed which collected evidence on the range of EEG reduction potential offered by different design and structural solutions. There exists a couple of works targeting design professionals offering calculations of EE, EG and sometimes, also other environmental impact categories, for a range of specific building components, relevant for various national contexts. Such examples include the calculations of environmental profiles for varieties of building parts relevant for the Danish market, performed by Marsh et al. in year 2000 [17] as well as the similar "Bauteilkatalog" in Switzerland [18]. These works facilitate the understanding of potentials at a building component level due to the information available on the composition of materials, but not the full impact of design choices at building level. In addition, they mainly focus on building material selection and naturally tend to cover common solutions already existing in the market. On the other hand, the broader range of EG mitigation strategies for all types of stakeholders has recently been reviewed by Pomponi and Moncaster [7].

Rather, the aim of this paper is to fill a knowledge gap by identifying and providing a collected and comprehensive overview of quantitative reduction potentials of the particular EEG reduction strategies which should be considered by the stakeholders engaged in, and with the capacity to influence the outcome of, individual building projects. That is, in particular designers, developers, contractors and their consultants. In this context, the following research questions are studied:

- What types of design and construction strategies do exist to reduce EEG in buildings?
- What are the EEG reduction potentials at the building level for different design and construction strategies?

Since the paper aspires to cover the wide range of potential design and construction strategies for EEG reduction, an in-depth analysis of each potential strategy will not be provided. Instead, it contributes with a classification of these strategies and with further analysis, seeks to identify their potential to reduce emissions at the building level. This is achieved by using existing evidence from the Annex 57 case studies, as well as, from other relevant literature. Thus, the paper will also explain the current status in the literature concerning the quantification of the potential to reduce EEG in individual buildings in relation to the various design and construction strategies.

2 Method

For the purpose of this paper, case studies at building level were sought with a view to illustrating the EEG reduction potentials when implementing different design and construction strategies. Early in the work of the IEA EBC Annex 57 Sub-task 4, a call was launched for case studies on EEG in buildings. One specific aim of the case study call was to collect case studies which identified or illustrated potential EEG design and construction strategies at building level. To motivate the submission of relevant case studies, potential design and construction strategies were initially defined by the author-group. They were drawn from the expert knowledge of the Annex 57 participants, from the literature, and later on, from the case studies themselves. For the purpose of establishing a broad range of possible strategies, strategies were defined that affect reductions throughout the lifecycle of a building, including beyond the system boundary of an individual building - see Figure 1. Apart from the call for case studies within the large Annex 57 group, international experts outside this group were also asked to provide case studies. The call was also disseminated at a few regional Sustainable Building Conferences.

Around 80 case studies were collected, categorized and analyzed from across the countries represented within IEA EBC Annex 57 [19],[20],[21]. The strength of using these case studies as an important source of information, is that first-hand in-depth information was available for the author group. In addition, case studies that otherwise would have been omitted if only journal papers were used for the analysis, have been analysed in this paper.

Nevertheless, since the submitted case studies only provided information about the EEG reduction potential of individual strategies at building level to a limited extent, an additional literature review was performed to gain more information. The aim of the literature review was to identify additional case studies, or other research, which investigated EEG reduction potentials of design and construction strategies implemented at building level in quantitative terms. A literature search conducted at the end of 2014, resulted in a list of several hundreds of papers in scientific journals or books. The literature was collected by a snowball approach, i.e. selecting relevant literature as suggested by scientific journals to be related to each consecutive paper reviewed. All abstracts of this list of literature were then reviewed, resulting in a selection of relevant papers for the purpose of this research. Finally, in spring 2017, an additional, but more limited, literature search was conducted which focused on finding new studies which particularly targeted strategies for which there was still limited case study evidence.

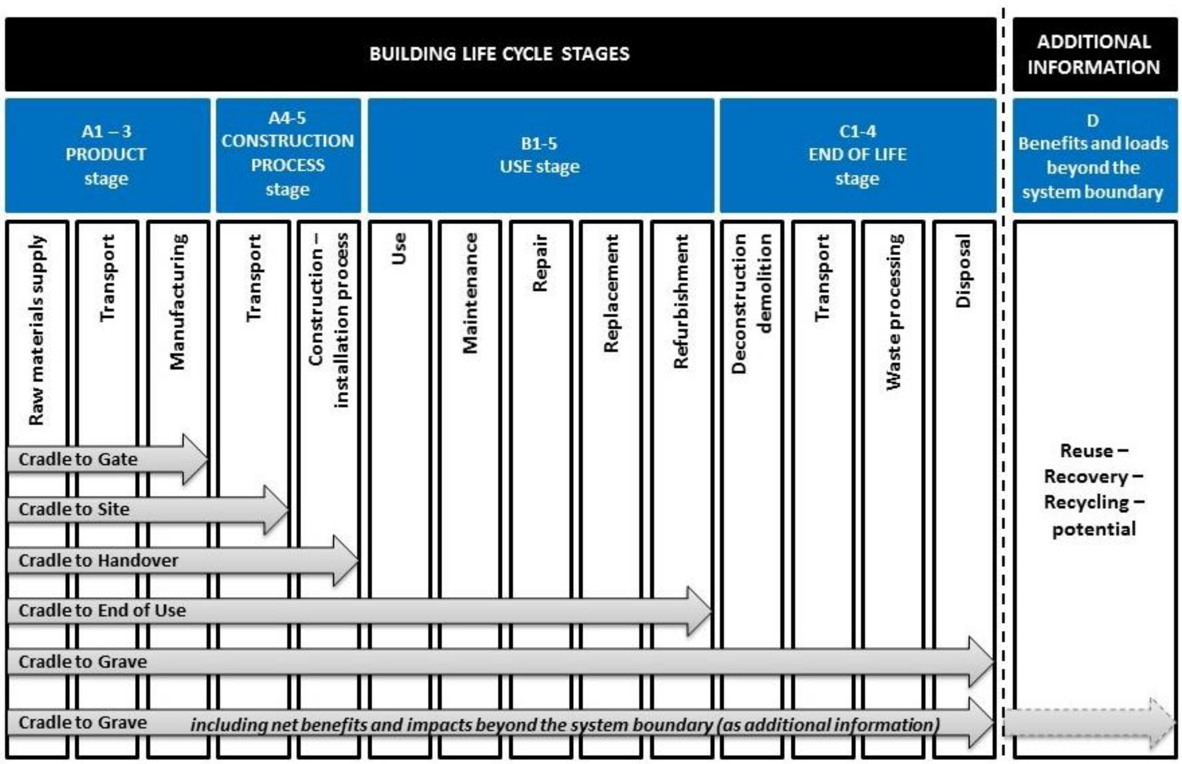

Figure 1. Building life cycle stages and modules included in the definition of embodied impacts, based on CEN 15978. Various system boundaries are included in literature covering embodied impacts of buildings, from cradle-to-gate, cradle-to-site, … etc. , as well as combinations in between [5].

After finalising the collection of Annex 57 case studies and cases from the literature, the reduction potentials for individual strategies were analysed and summarised. The quantitative results for EEG differ between the cases depending on data sources and calculation methods e.g. system boundaries, attributional or consequential approach, allocation principles used, etc. [20],[22],[23],[24].Therefore, such a case study analysis could not provide exact quantitative information, but could, nevertheless, give an indication of the proportion of the reduction potential. Finally, the case studies and the literature review were used to provide input into a summarised classification of design and construction strategies to reduce EEG in buildings.

Table 1 shows the full collection of Annex 57 case studies and the literature analyzed for the purpose of this paper. Within the table, the studies are categorised by the specific reduction strategies which were examined, and each strategy is discussed and illustrated with the help of the selected case studies and literature in the following section. The case study references in Table 1 relate to the numbering used for the Annex 57 case study collection [19] including a national abbreviation code together with a reference to background material if it exists. As stressed earlier, the strong influence of the calculation methodology, choice of system boundaries and geographical context is not addressed in detail here but can be cross referenced in the IEA EBC Annex 57 Subtask 4 report [20] and a paper by Nygaard Rasmussen et al. [22]. Therefore, it should be noted that as a result of the diversity of the methodologies used in the case studies and literature, the individual cases cannot be used to quantify reductions in general, but instead, illustrate the potential of different reduction strategies in various contexts.

Table 1. Identified EEG reduction strategies for implementation by building process stakeholders. For each strategy the table displays the case studies and literature of relevance for this paper. The case study abbreviation codes correspond to those used in the Annex 57 case study collection [19] which includes a nation code and, a reference to background material where available.

	Building type				
Strategies / measures	Residential (multi-family)	Residential (single family)	Office	School	Stadium
Using timber structures	SE2b, SE4 [25], SE7 [26], UK9 [27]	SE3 [28], UK5 [29], [30], [31]	SE5 [32]	UK7 [33]	
Using other "natural" materials		[34] [35] [36] [37]			
Using recycled and reused materials/components	[38]	DK2, CZ1, NO9, [39]	KR3 [40]		UK11 [41]
Using new, innovative materials/components	CZ2	[42]			
Light weight construction	CZ2, [43]	NO4 [44], [39]	NO2 [45]		
Optimising building form and design of lay-out plan	SE4 [25]	SE3 [28]	NO1 [46]		

Building/service life extension	SE7 [26]	DK3a,b [47], [48] Element level analyses: [49], [50]	JP4 [51] DK1 [52]		
Reusing building structures	No comparative studies, but related Annex 57 case studies include UK12, DK1, SE7, CH1-5, CH8-9, CH11-13, AT4, [53]				
Flexible/adaptable design		DK3c [47]	SE6 [54]		UK8 [55], UK11 [41], [56]
Reducing construction stage impacts	UK3, SE7 [26]	UK5 [29], [57], [34]		UK7 [33]	
Reducing end-of-life impacts			[58]	UK7 [33]	

3 Case study analysis: EEG reduction strategies for design and construction at building level

In the following section, the selected case studies deemed relevant for this paper are analysed with respect to illustrate EEG reduction potentials when implementing different design and construction strategies at the building level. In section 3.1, strategies are analysed, individually and consecutively, using evidence from relevant case studies and literature. The section ends up with Table 5, which summarizes the main conclusions drawn for each strategy based on the analysis. Section 3.2 then provides a systematic overview of characteristics of strategies and sub-strategies to enable a discussion about how they differ and, thus, their potential to realise EEG reductions in practice.

3.1 Analysis of individual EEG reduction strategies

3.1.1 Using timber structures

By far the most studied EG reduction strategy, both in the literature and in the Annex 57 case studies, is the substitution of mineral-based materials in the building structure with timber. Eight of the Annex 57 case studies covered comparisons between load-bearing, non-load bearing structures and foundations in timber compared to using other materials, for the same building under review. Table 2 displays EEG reduction potentials calculated in these case studies. It was found that only two studies covered EE, the first illustrated a substantial reduction for a timber building compared to a masonry one in **UK5**, but in the second one hardly any reduction at all when compared with a steel structure for the specific building under study (**UK7)**. Structures in timber compared to concrete display very large potential reductions in EG in **SE2b** and **SE4** (over 65%) and more moderate, but still significant, reductions were found in **UK9, SE3** and **SE5**. When only the façade material is changed to timber from either concrete or brick, moderate reductions in emissions are achieved as shown in **SE7** and **UK5**. Studies from the literature which also display high potentials for timber constructions include [30] and [31]. However, it should be noted that in the cases studied here, most only calculated EEG for the 'cradle-to-gate' or 'cradle-to-handover' system boundary, therefore, they did not identify potential differences regarding maintenance/replacement-related EEG during the use stage. Cases displaying large potentials for timber structures are generally found in the early-stage assessments, when the entire structure can be replaced by timber.

Table 2. EEG reduction potential in Annex 57 case studies comparing timber structures with other structural systems. Note that quantifications do not include carbon storage in timber, following the recommendations in Annex 57 to only report carbon storage separately [5].

Case study	EEG system boundary (see Fig. 1)	Level of building inventory	Timber is replacing…	EG reduction	EE reduction
At least load-bearing structure is replaced with wood (sometimes also foundations and non-load bearing structures					
UK5	Cradle-to-handover	Excl.building services, internal alls/doors/fittings and finishes	Masonry	34%	26%
UK7	Cradle-to-handover	Main structural elements	Steel	30%	1%
UK9	Cradle-to-handover	Main structural elements + elements affected by the choice of structural solution	Concrete	39%	Not studied
SE2b	Cradle-to-gate	Main building elements, both load-bearing and non-load bearing parts	Concrete	77%	Not studied
SE3	Cradle-to-gate		Concrete	27%	Not studied
SE4	Cradle-to-gate		Concrete	67%	Not studied
SE5	Cradle-to-gate		Concrete	28%	Not studied
Façade material is replaced with wood					
UK5	Cradle-to-gate	See above	Bricks	24%	26%
SE7	Cradle-to-grave	All components	Concrete	15%	Not studied

3.1.2 Using other "natural" materials

Apart from substitution to timber, a number of case studies from the literature exist which study other "natural", often locally sourced, materials like the use of earth, clay and straw-bales. The studies of Růžička et al. [34] and Havlik et al. [35] analysed the possibility of prefabricated rammed earth panels for both load bearing and non-load bearing interior walls in single family buildings. The analysis showed substantial reductions compared to using bricks, under the condition that the rammed earth was locally sourced. Sodagar [36] analysed the EG benefits of straw bales used as a material for load bearing walls. The straw variant had the lowest EG and was also found to be the cheapest of all the proposed variants. On the other hand, the use of straw required special design and construction details, since the straw bales needed to be properly protected from moisture and pests. Reddy [37] studied a conventional 2-storey brick and concrete building compared to constructing it in stabilized mud block masonry, resulting in a halving of EE in the latter. Other studies displayed reduction potentials for "natural" materials, but these were studied more at component level. These included, for example, the advantageousness of wood-based components compared to metal-based curtain walls [59], or wood fibre instead of mineral wool insulation as analysed in the Annex 57 case study **CZ3** [19] and clay plasters instead of cement or lime plasters as analysed by Melià et al. [60].

3.1.4 Using recycled and reused materials/components

Table 3 summarizes the results related to studies using recycled or reused materials and components. The substitution of virgin materials made with recycled or reused construction materials is a strategy gaining in importance in line with the emerging policies for the circular economy. For a few materials, such as steel and the use of recycled aggregates in concrete, this is already common practice, but for other materials, it is still uncommon. The Annex 57 case study **UK11** and Pavlů [61] looked at the effect of substituting the aggregate in cement with recycled aggregate, but neither noted significant EEG reduction potentials from this action directly which is due to it's limited contribution to the total EEG of the building. However, in the **UK11** case study, the substitution of cement by industrial by-products, such as, fly ash and slag was found to be very effective, and to an even greater extent in the study by Huberman and Pearlmutter [39]. Studies from the literature also display a high potential for cement substitution at material or component level as shown in Tyrer et al. [62], Pedersen et al. [63], O´Rourke et al. [64] and Garcia-Segura et al. [65].

In **CZ1**, the effect of substituting parts of the foundations and external walls with reused bricks was studied for a single family building. However, the reuse of materials, in this case, turned out to have only a negligible reduction effect in terms of emissions, since the walls, which were built of reused bricks, had to be strengthened by reinforced concrete columns. As a result, an interior coating consisting of gypsum boards also had to be introduced to hide the installations. Those additional structures have a high environmental impact and almost negate the positive effect of using reused bricks compared to the reference case. **NO9** also studied the substitution of re-used brick for a single family building, displaying clear reductions in EG, but these have not yet been assessed at the whole building level. The exploratory case study **DK2** analysed a concept called the "Upcycle" house, where materials are recycled or reused to the greatest extent possible. A reference single family building is compared to a building of the same size and design, where the use of upcycled materials was used to the maximum, for example, by using freight containers and paper wool for insulation, and also using upcycled windows and gypsum board.

The results showed that through the use of upcycled materials, the EEG could be considerably reduced, with 70-80 % depending on the indicator studied. In this case, an economic allocation of impacts from recycled materials was applied. Depending on the allocation factor used, the reduction potential can be slightly lower or higher. Finally, Cui et al [38], made a simplified calculation of the potential of improving a high-rise residential building in Hong-Kong by using recycled steel and slag cement to a certain extent, giving a reduction of 35% of embodied CO_2 emissions.

Table 3. Annex 57 case studies assessing EEG at building level, using recycled/re-used components and other new technologies.

Case study	EEG system boundary (see Fig. 1)	Level of building inventory	Technologies studied	EG reduction	EE reduction
Use of recycled/reused materials components					
UK11	Cradle-to-gate	Main building components	Recycled aggregate in concrete	Negligible effect	Not studied
			Fly-ash, slag in concrete	12%	Not studied
[61]	Cradle-to-gate + End-of-life stage (C1-C4)	Main building components	Recycled aggregate in concrete	Negligible effect	Negligible effect
[39]	Cradle-to-handover (A5-simplified)	Main building components	Fly-ash in concrete in 2/3 of external and internal walls	Not studied	Nearly 40%
CZ1	Cradle-to-gate	All but building services and internal fittings	Demo building with re-used bricks and part of foundation reused, compared to contemporary building of same size, etc.	Negligible effect	Negligible effect
DK2	Cradle-to-gate	All components	Demo building with freight containers and max. reused components, compared to contemporary concrete/masonry building of same size, etc.	80%	70%
Using new, innovative materials/components					
[42]	Cradle-to-grave excl. modules A4-A5 and C3-C4	Main building elements, both load-bearing and non-load bearing parts	Timber-concrete composite floor structure compared to reinforced concrete slab	30-45 % lower EG for timber-concrete structures	Negligible effect, but clear reduction if only load-bearing materials are compared
CZ2	Cradle-to-gate + End-of-Life processes	Only structural materials	Subtle high performance concrete frame with floor panels incl. wood shavings concrete, compared to	20%	About 15%

			monolithic reinforced concrete frame structure		

3.1.5 Using new, innovative materials/components

Emerging technologies can also contribute to materials and components which help to reduce EEG in buildings. Some case studies studied timber-concrete composite products, high performance concrete (HPC), and the use of building shell components with integrated photovoltaics. The reduction potentials had, however, only been calculated for the HPC studies as shown in Table 3.

In a case study by Hajek et al. [42], the embodied impact of two types of timber-concrete floor structures were compared to a traditional concrete slab and traditional wooden beamed floor structure. The traditional wooden beamed structure naturally has the lowest EEG but its inferior lateral rigidity and acoustic and fire safety properties limited its application in multi-storey buildings. The timber-concrete alternative clearly reduced the EG, but due to the high EE of the boards used in the non-load bearing layers, no effect on EE was seen at building level. When changing the concrete in the composite to the ultra-high performance option, both EG and EE is clearly reduced at building level compared to the reference case. The case study **CZ2** also provides an example of how ultra-high performance concrete (UHCP) can decrease EEG of the structure, since its high performance means that material quantities can be decreased significantly. The case study also included the strategy to mix wood shavings into the concrete for the floor structure. The combination of this concrete product for the floor structure and the ultra-high performance concrete (UHPC) in the frame, resulted in significant EEG reductions (15-20% depending on the indicator studied) compared to a reference building using only reinforced concrete which is the common solution used in the current market.

3.1.6 Light weight construction

One Annex 57 case study illustrated the EEG reduction potentials at building level which was achieved through decreased building weight. Table 4 displays the EEG reduction potentials calculated in these case studies. The six-storey building case study **CZ2** points to a substantial reduction potential for both EE and EG by reducing the use of concrete by using hollow core, compared to solid reinforced, concrete for the load-bearing constructions. Similar evidence is given in the studies by Huberman and Pearlmutter [39] and Lopez de Mesa [43]. The Norwegian case studies **NO2** and **NO4** both provide interesting examples of how careful planning to reduce concrete amounts in the foundations was achieved as a result of carrying lighter superstructures in timber. **NO4** implemented a strip instead of a raft foundation in concrete and also omitted the originally designed concrete pier base for the foundation, which reduced the concrete amounts by approximately 50% in the foundation. In case study **NO2,** it was estimated that the timber alternative structure of the office concept model caused 30% less weight (and associated emissions) which afforded the possibility to reduce the thickness of the basement slab and amount of concrete used. In the end, the combined effect of light-weight strategies in **NO2** with timber structure and reduced concrete in the thinner basement slab and walls led to almost 50% less EG compared to the original concrete and steel ZEB office concept model. Similar studies, investigating alternative foundations for light-weight superstructures include the "Lasagna foundation", which was developed in the Netherlands based on clay and layers of geotextile [66] and lumber-framed foundation walls which are pressure-treated to withstand decay from moisture and damage by termites [67].

Table 4. EEG reduction potential in Annex 57 case studies by implementing strategies to reduce resource use.

Case study	EEG system boundary (see Fig. 1)	Level of building inventory	Analysed reduction strategy	EG reduction	EE reduction
Light-weight construction					
CZ2	Cradle-to-gate + End-of-Life processes	Only load-bearing structure	Hollow core concrete is replacing solid concrete for load-bearing structure	20%	10%
[39]	Cradle-to-handover (A5-simplified)	Main building elements, both load-bearing and non-load bearing parts	Hollow core concrete is replacing reinforced concrete	Not studied	30%
[43]	Cradle-to-site	Only load-bearing structure	Hollow core concrete slabs are replacing solid slabs	12%	Not studied
Optimising building form and design of lay-out plan					
SE4	Cradle-to-gate	Main building elements, both load-bearing and non-load bearing parts	Square compared to rectangular form	6%	Not studied
Design for flexibility/adaptability					
DK3c	Cradle-to-gate + modules B4-B5, C3-C4	Main building elements, both load-bearing and non-load bearing parts	Easily reusable external wall system (in case of expanding the housing area) + internal wall system easy to move to change lay-out of rooms, compared to reference house.	Around 50 % reduction in module B5 EG compared to reference building	More than 50 % reduction in module B5 EE compared to reference building
UK8/UK11	Cradle-to-gate	Main building elements	Design for easy dismantling to enable efficient change in number of seats	30 000 tons CO_2-eq compared to original design (more than 50% of this	Not studied

				reduction is associated with flexible design measures	
Service life extension					
JP4	Cradle-to-gate + replacements (B4)	Main building elements	Extending building service life with 40 y by earthquake resistant construction	20-30%	30-35%
DK3a-b	Red. Potential only relate to modules B4-5	Main building elements, both load-bearing and non-load bearing parts	Extending building service life by 30 y due to more durable structural materials and overhangs to protect windows, etc.	Approx. 50 % of recurring EG compared to reference building	Approx. 50 % of recurring EE compared to reference building

3.1.7 Optimising building form and design of lay-out plan

The design of lay-out plan and building form is discussed in this context as the ability to reduce material consumption (and associated GHG emissions) due to a material and space-efficient design. Three Annex 57 case studies illustrate this strategy, as shown in Table 4. The early stage case study **SE4** found a 6% EG reduction potential when designing a multifamily building with square compared to rectangular form. Another issue studied in two Annex 57 case studies (**SE3** and **NO1**) was how to optimize useful space in the building and how this correlates to the potential for EEG reduction. These cases, however, do not reveal absolute EEG reduction potentials, but rather offer examples of how added function, in the form of a more useable and space efficient floor area achieved by the redesign of the lay-out plan, was found to lead to reduced EEG per m^2 or per person.

3.1.8 Building/service life extension

The case study **JP4** explored the influence on EG by extending the service life from 60 to 100 years for a planned library in Tokyo (Japan). The implemented strategies included increasing the durability of it's reinforced concrete construction, as well as, increasing it's earthquake-resistant strength. It was found that the combination of incorporating both measures led to an increased use of concrete and reinforcing rods, however, the life time extension from 60 to 100 years, nevertheless, led to a significant reduction in EEG throughout the whole life cycle of the building, that is; in the region of 20 - 35%, as shown in Table 4. In the Danish case study **DK3a-b,** two different designs for a single-family building with a low maintenance need were developed and compared to a Danish reference building. The first example was designed to maximize the use of durable building materials, such as, bricks and tiles in the main structure. The second example is a wooden construction with glass cladding used in order to protect the wood. In both cases, an overhang was included in the design to protect the weaker building components such as windows from weathering. For both building designs, the service life of the windows is estimated to increase from 25 years to 40 years compared to the reference building. Translated to a reduction potential, these strategies implemented on the particular case corresponds to recurring EEG reduction in the region of 50%, compared to the reference building. In addition, a number of studies have examined the impact of variations of service life on EEG. Rauf and Crawford [48] analysed the influence on EE from replacement of components and materials in order to extend the service life from 1 to 150 years for a single family building. Grant et al. [49] and De Castro et al. [50] did similar studies but the comparison was for individual building elements only. All of the studies come to the consensus that full life-cycle EEG depends strongly on the frequency of replacing major materials in the building envelope, like brick walls, etc. Similarly, the Annex 57 case studies **DK1** and **SE7,** display how the proportional impact of replacements, namely module B4, increases with the increase of the reference study period. Thus, they demonstrate the importance of considering design approaches as implemented in **DK3a** described above, in particular for the construction of buildings specifically designed for a long life.

3.1.9 Design for flexibility/adaptability

Another, related, way to increase the service life of a building, is to integrate adaptable design approaches from the beginning, in order to limit extra resource use associated with a future change in function of a building. A number of earlier studies have indicated that refurbishment and replacements may represent a high proportion of the full life EEG if change of use during the life time is taken into account [68], [69], [70]). Similar evidence is given in the Danish case study **DK3a** and the Swedish study **SE6**. Both case studies clearly consider how user-driven refurbishments can result in, as much as, 50% of the total EG during a reference study period of 50 years. Two Annex 57 case studies include assessments of EEG reduction potential in relation to flexible design (see Table 4). The Danish case study **DK3c** for a 2-storey single-family building was designed from inception to consider altered room distribution, including the kitchen, and to increase the usable living space in the future. Key design strategies implemented in the building include the use of external wall elements and an internal wall system which can easily be reused or moved. Compared to the Danish reference building, the EEG connected to the refurbishment module (B5) resulted in a halving of emissions. The case study **UK8** describes the flexible design used in the London 2012 Olympic stadium. The chosen design consisted of a structural frame made up of a series of parts which could easily be deconstructed, as well as, incorporating a bolting method to facilitate the dismantling of the precast seating units [56] in order to substantially reduce the number of seats for the arena after the Games. This can also be looked upon as an example of “design for disassembly” but the reduction potential is rather seen as the benefits from recycling and reuse of materials in the product stage of future buildings. Thus, the easily dismantled seating units of the Olympic stadium (**UK8**) will also potentially reduce EEG in future buildings even though such quantifications were not made in the current case study.

3.1.10 Reusing building structures

The reuse of older building structures instead of constructing “virgin” buildings can also be seen as a strategy to reduce resource use and the associated EEG of the product and construction process stage (modules A1-A5). A case study of the EE savings achieved through reusing the structure of a single-family building compared to demolition and subsequent new-build was performed by Gaspar and Santos [53], who found a potential EE reduction of 22%. Within the Annex 57 case studies, a number of case studies focus on calculating the impacts for major refurbishments. The main alternative to such major refurbishments is to construct a new building on the same site. Unfortunately, none of the cases make direct comparisons between the EEG of a refurbishment case compared to a new-build alternative. However, for these relevant Annex 57 cases the product stage EE (modules A1-A3) ranged from around 1700-4600 MJ/m^2 (compared with the product stage for Annex 57 new builds of 940-15650 MJ/m^2) and the product stage EG between 65-380 kg CO_2-eq/m^2 (compared with 160-640 kg CO_2-eq/m^2 for Annex 57 new builds) [19]. These figures indicate substantial potential savings from reusing building structures.

3.1.11 Reducing construction stage impacts

The construction process stage (transport of products and equipment to site and on-site processes, including on-site waste production, modules A4-A5 in Fig 1) is commonly assumed to represent a much smaller proportion of life cycle-EEG than the other stages, which is one reason why building level case studies often omit these impacts. However, of the eleven Annex 57 case studies that did include calculations of this stage, the impact typically represented 14% of the total EG for the building stage (A1-A5) which is not insignificant. Only five Annex 57 case studies included EE calculations of the construction stage impact, which in these cases vary between 6 to 38 % of the total EE. A few of the Annex case studies (**SE7, UK3, UK5**) display the breakdown of construction stage impacts. On-site electricity use and production of wasted materials, as well as, transport of products to site typically dominate the construction stage EG. However, emissions during construction stage can vary greatly, as displayed in the case study **UK3** on 11 different housing developments. Important variables affecting the construction stage EG were found to be the type of energy used and whether construction takes place during the heating season or not.

Limited examples exist, though, of cases displaying clear reduction potential in terms of impacts at the construction stage. In the case study **UK7,** a timber and a steel structural alternative are compared, showing that the timber alternative requires the use of a crane and cherry-picker on-site, as well as, overseas transport of timber to the site which leads to an increase in construction process stage EEG compared with the steel alternative. Similarly, a number of literature case studies come to the same conclusion that EEG associated with transport to site (module A4) can have a substantial impact on total EEG when large masses (like pre-fabricated, modular building components) need long-distance transports [57], [34], [71]. However, for the UK7 example, when looking at the EG for all stages A1-A5, the timber structure is still more advantageous. The two structural solutions have approximately equal EE for the studied case.

The case study **UK5** looked into contribution to EEG of wasted material during the construction process. In this case study, wasted material represents a significant share of the total EG of this building (14%). However, the **UK5** building structure consisted of a pre-fabricated timber frame, resulting in small contribution to the total waste related EG generated on-site. Thus, the case study concludes that increased use of pre-fabricated components could be important to reducing waste generation associated with the construction stage. A case study by Quale et al [57], compared three modular options of a single family home with five conventional options. On average, the study displayed a slight advantage for the modular cases when comparing the on-site energy use of the conventional homes with those of the modular homes. Energy use includes the energy used in the factories, on-site energy and energy to transport modules to site. Nevertheless, one of the modular cases had high emissions from energy use in the factory due to the high electricity usage and heating with oil [57].

3.1.12 Reducing end-of-life impact

Similar to the construction stage impacts, the EEG associated with the end-of-life stage (module C) commonly represents a smaller share of the total, and is therefore omitted in some case study calculations. No studies were found that displayed reduction potentials during the end-of-life processes. In the Annex 57 case studies, the main topic studied in this stage is the impact of waste treatment in combination with the recovery potential. The latter leading to benefits outside of the system boundary of the individual buildings. In case study **UK7**, the steel and timber load bearing structures are compared with an emphasis on their recovery potential. The end-of-life scenario for the timber structure includes combustion with energy recovery in which it was assumed that the timber biofuel would offset CO_{2eq} emissions associated with burning natural gas. For the steel structure, recycling is considered as the most probable scenario and EEG savings were calculated based on a methodology developed by the International Iron and Steel Institute [72], in which credits are awarded to steel for it's recyclability potential. The recovery potential for the timber structure scenario in terms of EEG is very high. Recycling of steel, while better than landfilling, has quite a high environmental impact, and the recovery potential is limited. Therefore, the reuse of steel components was not studied, but it is acknowledged that it could possibly significantly increase the recovery potential of steel. In the research by Junnila [58], the life cycle of 15 buildings was studied with five different end-of-life scenarios taken into account for each building The scenarios differed with respect to the ratio of recycled material. The main conclusion is that for the scenario with a small ratio of recycling, there is no benefit and that the impact indeed is higher than that for the scenario without recycling, since transport of the material for recycling causes a higher impact than that for landfilling or incineration. For scenarios with higher recycling rates, the impact significantly decreases.

Table 5. Summary of lessons learnt from the case study analysis regarding EEG reduction potentials.

Using timber or other natural materials A number of case studies demonstrate that substitution to timber in large building components, such as structure or façade, has a relatively high potential to reduce embodied greenhouse gas emissions. However, the case studies also show large variations in reduction potentials, from 27-77%, depending mainly on the different structural solutions chosen. Most case studies only cover 'cradle-to-handover' EEG, displaying the need for more studies on potentially alternative conclusions when assessing full-life cycle EEG. A limited amount of studies display high potential for EEG reduction using traditional materials, like rammed earth or straw-bale. However, data on EEG for traditional natural materials is limited and thus, not well-considered in reduction assessments to date.
Using re-cycled/re-used materials and components The effect on EEG reduction of re-cycling and re-use is variable with cases displaying a clear, and sometimes, large reduction potential. The Danish case DK2, showed that in order to achieve a

significant reduction of EEG, a complex and individual planning process had to be applied for the building project. This and other studied cases, clearly show that a lot of effort still needs to be put into project planning development, assessment of the quality of recycled material regarding functional and/or structural requirements, as well as, improving logistics, capability and accessibility of recycling facilities, so as to realize EEG reductions in line with circular economy ambitions. Also, there still exist ambiguities in calculation methodologies regarding impact allocation for re-cycled and re-used materials, which currently limits the possibilities to better establish the range of reduction potential due to this strategy.
Using new, innovative materials and components A number of case studies were analysed which showed a few examples of EEG reductions obtained when implementing new innovations for building structures. This includes the use of wood-concrete composites and high performance concrete products that can substitute structural elements in concrete, as well as building integrated PV panels which do not need additional construction elements when installed. However, in some cases new, innovative materials cause higher impacts, partly because production methods are still immature.
Light-weight construction The results of the Czech and Norwegian case studies, in which solid concrete was replaced by hollow core concrete and strip foundation respectively, as well as, component level case studies, such as, the one performed by Castro et al. [50], reveal large reduction potentials as long as basic functional requirements, such as strength, are fulfilled. Therefore, this strategy also needs careful consideration in the planning process, so as, not to embed risks for decreasing the service life of the building, and consequently, increase the full-life EEG. For example, the slab-on-ground construction technique is technically preferable to the strip foundations with the ventilated space below, as implemented in NO4. Typically, building materials in the slab-on-ground construction are less exposed to the elements, and are therefore less prone to rot or decay, thus extending the service lifetime of the building component.
Optimising building form and design of plan layout All three case studies which were analysed show that keeping a building as compact as possible reduces EG. In two Swedish case studies, the reduction is moderate, however, compared to reductions obtainable by material choice,which was also analysed in these cases. Improving the space efficiency of a buildingby avoiding unnecessary open spaces and keeping floor area per person within limits on the other hand, is a key driver for reduced EEG and is more effective than material choice for reducing total EG.
Extension of building service life Extending the service life of buildings can be an important strategy to decrease EEG, as demonstrated by a number of case studies. However, a Japanese case study (JP4) also shows that the design for a building with a long service life can imply, in practice, a corresponding increase in the cradle-to-gate EEG as a result of the additional material use in order to ensure increased durability of the structure. The Danish case study DK3a provides examples of design measures to prolong the service life of exposed surfaces, namely windows, leading to around 50% reductions in EG associated with replacements compared to a reference building. Nevertheless, the cases and literature analyses clearly show that increasing cradle-to-gate EEG with the intention of extending the service life is only feasible if the building indeed meets the theoretically longer service life. It is therefore recommended to consider this approach when it is likely that the building will last for more than 50 years. It should also be noted that a likely value for an assumed service life depends on the building function, market

situation and other determining factors.
Adaptable/flexible design Two cases were analysed which display the potential for future EEG reduction in refurbishment or building alteration due to a change in function. The Danish case DK3,is an interesting example since careful consideration in design meant that the integration of adaptable design solutions did not increase cradle-to-gate EEG. Otherwise, Russell and Moffatt [73] recommended that adaptable design approaches should only be used for buildings in which future changes in function are anticipated. One such example includes commercial office buildings in attractive locations, like the one studied in Swedish case study SE6. In the specific case of the Olympic Stadium in London (UK8 and UK11), adaptable design was implemented to easily disassemble and thus, reduce the number of seats after the Games which formed part of an effective design strategy that reduced the EG of the original design by almost one quarter.
Reduction of construction stage impacts The few Annex 57 case studies which do include the construction stage (modules A4-5), suggest that these contribute to a much smaller share of the total EEG compared to the other modules, such as, cradle-to-gate EEG. However, the picture is not at all clear and there exist exceptions, meaning that there is certainly potential for reduction, with impacts found to vary due to the type of energy used, whether construction takes place during the heating season, energy efficiency in construction site huts, and site waste management. The difficulties in getting input data in building projects related to construction site energy and fuel use, so far, limits the possibilities to better understand reduction potentials at building level from improved construction site processes. A few studies indicate an advantage for using pre-fabricated components to reduce EEG. On the other hand, when using pre-fabricated components it becomes more important to also consider the impact on transports to site since the decreased EEG due to reduced on-site construction waste may be outweighed by an increase caused by the transport of pre-fabricated elements to site. It is also recommended that transport to site should not be neglected by default in calculations. That is, the transport of high masses of materials in long distances can contribute to a substantial share of the life cycle EEG.
Waste recycling in end-of-life Predicting future waste and recycling practices remains uncertain, however, recycling of waste is expected to increase with current policies, implying that more consideration should be given to the selection of materials and design for future reuse and recycling. Quantifying recovery potentials based on case studies still remains a concern due to the variations in methodologies applied.

3.2 Classification of EEG reduction strategies in buildings

The previous section describes the wide array of design and construction strategies that can be implemented in the building process in order to generate EEG reductions of various levels. This review provides a number of insights that enable a more systematic and coherent understanding of the potential of various design and construction strategies to reduce EEG in buildings. Table 6 provides a systematic overview of characteristics of strategies and sub-strategies, taken up in section 3.1, which forms the basis for the following discussion on the differences between strategies and challenges for their implementation.

Table 6. Classification of design and construction strategies for EEG (embodied energy and greenhouse gas emissions) reduction in buildings.

	EEG reduction principle		**Building process stage in which strategy is mainly implemented**			**Life cyclestage (see Fig. 1) in which reduction potential is realized**	**Actual or scenario-dependent reduction**	
Strategy	*Substi-tution*	*Reduc-tion*	*Design Stage*	*Construction stage*	*Other*		*Actual*	*Scenario-dependent*
Using timber or other “natural” materials	X		X			A1-A3	X	
Using recycled/reused materials/components	X		X	X		A1-A3	X	
Using new, innovative materials	X	X	X			A1-A3	X	
Using new, innovative structural components	X	X	X			A1-A3	X	
Light-weight – hollow core/strip		X	X	X		A1-A3	X	
Light-weight – thinner foundation		X	X	X		A1-A3	X	
Optimising building form		X	X			A1-A3	X	
Optimising useable floor-area			X					IF more people use it
Extension of building service life		X	X		Use stage when time for maintenance and/or refurb.	B4, B5		IF long life
Reusing building structures		X			Use stage when time for refurb.	B5	X	
Design for flexibility/adaptability		X	X			B5		IF changed function
Design for disassembly		X	X	x		D		IF components will be reused
Design for low maintenance need		X	X		Use stage when time for refurb.	B2, B3		IF maintained as expected
Optimizing energy use in construction process	X	X		X		A5	X	
Minimizing on-site wasted material		X		X		A5	X	
Minimizing emissions from transports to-site	X	X	x	X		A4	X	
Waste recycling in end-of-life		X			End-of-life stage	C1-C4	X	IF recycled as expected

Firstly, two main overarching principles for EEG reduction can be seen, that is to substitute materials and components with ones with less EEG, or to reduce the quantities of materials or components used, while maintaining the same function. In Table 6, a few strategies make use of both principles, mainly due to how they are formulated. For example, to optimize energy use in construction relates to both energy-efficiency measures and type of fuels or energy carriers used.

Another way to characterize EEG reduction strategies, is in relation to *when* in the building process the strategy is put in place. This, in turn, suggests which stakeholders might be responsible for considering and implementing the strategy in the building process. In particular, Table 6 illustrates the importance of the design stage for many of the identified strategies. Since, usually the majority of the EEG in buildings is associated with building material production [19], it is evident that developers, designers and consultants have an important role in engaging in both substitution and reduction strategies in early design of both new-build and refurbishment projects. However, Table 6 also makes it clear that contractors in the construction and/or end-of-life stages as well as property owners during the operation stage should consider a number of reduction strategies.

Table 6 displays the wide range of strategies that can produce reductions in the first life cycle stages, but also shows that certain strategies are, for example, effective in the construction process and in the later life cycle stages of a building. It thus reveals the importance of assessing environmental reduction potentials of buildings through a life cycle perspective, since interesting and useful reduction strategies might be missed if only the product stage is assessed. Related to this topic, a distinction can be made between strategies which have already affected the EEG at the handover of a new building or building refurbishment, or those which will affect the EEG in the future. Some strategies, rather than directly reducing EEG, incorporate a potential higher environmental performance in the future through building design. This issue has been discussed earlier in the literature, for example, within the field of indicators for sustainability assessment and certification of buildings as described in Wangel et al [74]. In these works, 'performance indicators' are often promoted above 'feature indicators'. Performance indicators measure actual impacts, whereas feature indicators measure, for example, design features which aim to lead to a better building performance in the future. Flexible and adaptable design is a typical example. Adaptable design is integrated as a feature which has the ability to lead to lower full life-cycle EEG. If the building function is changed in the future, adaptable design measures may lead to reduced waste production as well as reduced amounts of new materials used. If not, the reduction potential will not be realized. One example is given in the Japanese case **JP4**, in which physical measures were taken to improve earth-quake resistance. This action leads to an increase in cradle-to-gate EEG in order to decrease full-life EEG. In this particular context, it is likely that the EEG reduction will be realized. However, to perform such measures in general may instead lead to increased full life-cycle EEG since design potentials may not be used in practice. In this regard, the Danish case study **DK3** of the "adaptable building" is therefore an interesting example of how adaptable design has been integrated into the design, so as to reduce full life-cycle EEG without, at the same time, leading to higher cradle-to-gate EEG.

Finally, it is also important to make a distinction between actual, physical actions taken to reduce EEG, for example, adding material for a longer service life in **JP4**, compared to theoretical actions or assumptions taken when setting up the use-stage scenarios in the calculations. For example, both **DK1** and **SE7** illustrate how EEG per m^2 is reduced if a longer life span is assumed, but in these cases no change in design was made to promote a longer life span.

The case studies which were analysed also reveal that there still exist variations and ambiguities in the assessment methodology which have an impact on reported reduction potentials. This issue is discussed in detail in another paper by Nygaard Rasmussen et al., [22] and is important to refer to here as well. For example, the potential of using bio-based structures depend on whether carbon storage is included or not in calculations. For the analysis of this paper, it was possible to exclude carbon storage in all cases reported here to avoid misinterpretation. Regarding the potential of using recycled and reused components, as well as, potentials in relation to different waste scenarios during the end-of-life, a variety of allocation procedures and system boundaries are used in the case studies. Similarly, the set-up of future scenarios in relation to design for adaptability and how functions are assessed can result in varying conclusions regarding the extent of reduction potential. This is illustrated by the Swedish and Norwegian cases (**SE3** and **NO1**) regarding the design of the lay-out plan. Since the cases presented in the paper also originate from different countries, it shall be noted that individual quantifications of reduction potentials also depend on the particular country-specific data used for calculations. Of particular importance is the electricity mix used for manufacturing of construction materials. The regional variability of this mix will, thus, play a role for the quantified reduction potential of individual mitigation strategies in different countries.

4 Concluding discussion

Until recently, the building and construction sector has focused on the reduction of operational energy use in buildings. However they have now started to show an interest in the integration of life cycle thinking in building design and construction. A better understanding of the EEG (embodied energy and greenhouse gas emissions) reduction potentials of different design and construction strategies implemented at building level is therefore highly topical and urgent. This paper presents a systematic analysis of relevant studies from the case study collection of IEA EBC Annex 57, as well as, of additional scientific literature, in order to describe and evaluate the current knowledge in this area. The resulting contribution is a detailed compilation and characterization of the multiple strategies available.

The results show that the strategies can be divided into several distinct categories. These strategies also relate both to the life cycle stages they impact, and to the stakeholders who have the principal responsibility. The first, and arguably simplest, category is concerned with the reduction of ‘initial’, or ‘cradle to gate’ EEG, in modules A1-3. For these stages the key strategies are either based on the substitution of high-EEG materials with low, or on the more efficient use, or reduction, of materials; the responsibility for these changes lies chiefly with designers and their clients. The second category relates to reductions of ‘recurrent’or in-use stage EEG, in modules B2-5, and includes strategies which offer a potential future reduction of EEG through choices made at the building design stage. This category includes increased durability of components and flexibility for future changes of use. However while these strategies may offer substantial future reductions, they will only be realized in particular scenarios, and therefore they are the responsibility both of the designers, and of the building owner-occupiers who will make the future decisions. They need to be considered in relation to the expected service life and the probability of future building changes, and caution should be exercised if they require an *actual* increase in 'initial' EEG in order to achieve a *potentially* lower whole-life EEG. The third category is the reduction of EEG in the construction (A4-5) and deconstruction (C1-4) stages. This includes strategies such as minimizing construction energy and waste, reducing transport distances of materials to and from site, and ensuring energy-efficient waste processing. The responsibility is predominantly that of the contractors and their supply chain, although the effect of policy makers on waste treatments can also be considerable.

The following key recommendations can therefore be drawn from this paper. For designers and clients:

- Replacing structural components with timber, or other bio-based or low embodied impact materials, where structurally feasible has been shown in numerous cases to reduce embodied impacts by a substantial percentage.
- The use of recycled or recovered components and materials has considerable potential to reduce EEG. However at present the manufacture, testing and supply chain logistics are immature, leading to difficulties in employing this strategy at scale.
- Innovative materials and components such as wood-concrete composite members are promising in this area, but again immaturity of the manufacturing processes means that reductions cannot yet be fully realised.

For contractors:

- Minimising site waste and energy use both in construction and demolition, ensuring materials are locally sourced where possible, and separating and recycling or processing waste to maximum efficiency, will all reduce the life cycle EEG. While these stages do not represent a high percentage of the whole life EEG of a building, small changes in practice can make a substantial difference to the EEG impact of these particular stages.

For owners and occupiers, as well as designers:

- Both durable buildings which include components with long service lives, and adaptable buildings which can be used in different configurations at different times, can lead to lower embodied impacts over the life of the building. However the designers have the responsibility to ensure that these options are more likely than not to be used – that is, that the building will be retained for its extended service life, and is likely to need the potential adaptations – while the owners have the responsibility to ensure that the options that are taken through the life of the building follow the initial design intent.

It is also clear from the analysis that EEG reduction considerations need to be taken as early as possible in the design (and construction) process.

However, the analysis also reveals that there are still only limited studies which calculate the reduction of EEG from most of these strategies, and far more are needed. In addition to an increased academic focus on calculation, in order to drive EEG reduction in buildings there is also a need to promote the development of innovative, low-EEG building materials and products. Policy-makers can also play a role in reducing EEG, for instance through regulating waste processing and encouraging reductions in life-cycle impacts through building regulations.

While it should be noted that the actual EEG savings illustrated in this collection of studies are only applicable to each specific case, importantly this multiple cross-case analysis has provided rigorous evidence of the considerable potential to reduce embodied impacts in the design and construction of new and refurbished buildings. It has highlighted a wide array of strategies which should be considered, and has identified which stakeholders have responsibility for each. If the strategies presented in this paper were to be systematically integrated into all buildings and processes, they would contribute significantly to climate change mitigation and increased resource efficiency.

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Appendix A: Overview of all case studies analysed in IEA EBC Annex 57 [19]

Case study	Database	RSP	Product stage			Construction process stage		Use stage					End-of-Life				Next product system	Main concept	Type	Page number in Annex 57 Case study report [19]
			Raw material supply	Transport to manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery or recycling potential			
Austria																				
AT1	baubook eco2soft	100	x	x	x						x	x						New	Office	
AT2	baubook eco2soft	100	x	x	x						x	x						New	Residential	
AT3	baubook eco2soft	100	x	x	x						x	x						New	Office	
AT4	EcoBat	60	x	x	x						x		x			x		Refurbishment	Residential	91-100
AT5	Baubook eco2soft	100	x	x	x						x	x						New	Residential	
AT6	Ökobau 2009	50	x	x	x						x				x	x		New	Office	
AT7	baubook eco2soft	100	x	x	x						x				x	x		New	Residential	
Switzerland																				
CH1	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	School	179-185
CH2	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	School	186-194
CH3	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	School	195-203
CH4	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	School	204-212
CH5	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	School	213-220
CH6	EcoInvent 2.2	60	x	x	x						x				x	x		New	School	
CH7	EcoInvent 2.2	60	x	x	x						x				x	x		New	School	
CH8	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	Residential	239-247
CH9	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	Residential	248-256
CH10	EcoInvent 2.2	60	x	x	x						x				x	x		New	Residential	
CH11	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	Residential	265-273
CH12	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	Residential	274-282
CH13	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbishment	Residential	283-291
CH14	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential	
CH15	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential	
Czech republic																				
CZ1	Envimat	60	x	x	x													New	Residential	307-311
CZ2	Ecoinvent 2.2	100	x	x	x	x	x						x	x	x	x		-	Material	312-316
Germany																				
DE1	Ökobau 2011	50	x	x	x						x				x	x	x	New	School	
DE2	Ökobau 2011	50	x	x	x						x				x	x	x	New	School	
DE3	Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential	
DE4	Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
Denmark																				
DK1	PE int	50	x	x	x						x				x	x	x	New	Office	339-345
DK2	PE int	50	x	x	x													New	Residential	346-350
DK3a	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential	351-357
DK3b	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential	351-357
DK3c	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential	351-357
DK3d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential	
DK3e	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential	
DK4a	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4b	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4c	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4e	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4f	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	
DK4g	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office	

Case study	Database	RSP	Product stage			Construction process stage		Use stage					End-of-Life				Next product system	Main concept	Type	Page number in Annex 57 Case study report [19]
			Raw material	Transport to	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery or recycling potential			
Italy																				
IT1	Various	-	x	x	x	x	x		x					x		x		-	Material	
IT2	EcoInvent	50	x	x	x				x		x		x	x	x	x	x	New	Residential	
IT2	EcoInvent	50	x	x	x				x		x		x	x	x	x	x	Refurbishment	Residential	
IT3	EcoInvent	70	x	x	x	x	x		x			x	x	x			x	New	Residential	
IT4	(Not specified)	-	x	x	x	x												-	Material	
Japan																				
JP1	IO table Japan	90	x	x	x	x	x		x		x							New	Residential	
JP2	(Not specified)	-	x	x	x													New	Residential	
JP3	Various	60	x	x	x	x	x				x	x	x	x	x	x		New	Residential	
JP4	IO table Japan	60/100	x	x	x													New	Office	425-429
JP5	IO table Japan	60	x	x	x	x	x	x		x	x	x	x					New	Office	
JP6	IO table Japan	50/100	x	x	x	x												New	Office	
JP7a		-	x	x	x	x	x				x	x	x	x				Refurbishment	Office	
JP7b	IO table Japan	-	x	x	x	x	x				x	x	x	x				New	Office	
South Korea																				
KR1	KOR LCI	30	x	x	x	x					x				x	x		New	Residential	
KR2	KOR LCI	30	x	x	x						x				x	x		New	Residential	
KR3	KOR LCI	50	x	x	x	x	x									x		New	Office	457-461
KR4	KOR LCI	30	x	x	x						x				x	x		New	Residential	
Norway																				
N01	EcoInvent	60	x	x	x						x							New	Residential	468-481
NO2	EcoInvent	60	x	x	x						x							New	Office	482-490
NO4	EPD	60	x	x	x	x												New	Residential	491-496
NO8	EcoInvent	60	x	x	x						x							Refurbishment	Office	
NO9	EcoInvent	60	x	x	x						x							New	Residential	503-510
Sweden																				
SE1	Swedish IO data	1	x	x	x	x	x		x	x	x	x	x					-	Sector	
SE2a	EcoInvent, BECE	50	x	x	x													New	Residential	
SE2b	EcoInvent, BECE	50	x	x	x													New	Residential	522-528
SE3	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential	529-533
SE4	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential	534-538
SE5	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Office	539-543
SE6	EPD, Ökobau 2013, EcoInvent, KBOB	1									x							Refurbishment	Office	544-548
SE7	IVL Miljödata, EPDs, EcoInvent, KBOB, ICE	50	x	x	x	x	x			x		x	x	x	x	x		New	Residential	549-556
United Kingdom																				
UK1	-	-																-	Policy	
UK2	BATH ICE, ECEB	N/A	x	x	x	x	x							x				Refurbishment	Residential	
UK3	(Not specified)	N/A					x											New	Residential	569-574
UK4	BATH ICE, ECEB	68	x	x	x	x	x			x	x	x	x	x	x	x		New	School	
UK5	ICE, EcoInvent, USLCI	20	x	x	x	x	x											New	Residential	582-586
UK6	-	-																-	Policy	
UK7	Bath ICE	60	x	x	x	x	x		x	x			x	x	x	x	x	New	Sports hall	598-603
UK8	-	-																-	Policy	604-610
UK9	EPD, ELCD, Industry data	-	x	x	x	x	x						x	x	x	x	x	New	Residential	611-615
UK10	-	-																-	Tools	
UK11	-	-																-	Policy	620-624
UK12	BATH ICE, Green guide to specification, ECEB	60	x	x	x	x	x		x	x	x	x	x	x	x	x		Refurbishment	Residential	625-629

References

[1] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A Roadmap for moving to a competitive low carbon economy in 2050, European Commission, Brussels, 2011.

[2] European Union, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on the energy performance of buildings, Official Journal of the European Union (2012) L315 1-56.

[3] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review; Renewable and Sustainable Energy Reviews 29 (2014) 394-416

[4] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs. embodied emissions in buildings—A review of current trends, Energy Build. 66 (2013) 232–245. doi:10.1016/j.enbuild.2013.07.026.

[5] T. Lützkendorf, M. Balouktsi, R. Frischknecht, IEA-EBC Annex 57 Subtask1 report - Basics, Actors and Concepts, 2016. http://www.iea-ebc.org/projects/completed-projects/ebc-annex-57/

[6] M. Wallhagen, M. Glaumann, T. Malmqvist, Basic building life cycle calculations to decrease contribution to climate change – Case study on an office building in Sweden, Build. Environ. 46 (2011) 1863–1871. doi:10.1016/j.buildenv.2011.02.003.

[7] F.P. Pomponi, A.M. Moncaster, Embodied carbon mitigation and reduction in the built environment: the evidence, Journal of Environmental Management 181 (2016) 687-700.

[8] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article, Energy Build. 39 (2007) 249–257. doi:10.1016/j.enbuild.2006.07.001.

[9] Boverket, Byggnaders klimatpåverkan utifrån ett livscykelperspektiv - Forsknings- och kunskapsläget, rep. 2015:35, Boverket, Karlskrona, Sweden, 2015.

[10] C. De Wolf, F. Pomponi, A.M. Moncaster**.** Current industry practice in embodied carbon calculation, Energy and Buildings 140 (1) (2017) 68-80.

[11] UNEP, Towards zero-emission efficient and resilient buildings - Global status report, 2016. https://wedocs.unep.org/bitstream/handle/20.500.11822/10618/GABC-Report_Updated.pdf?sequence=1&isAllowed=y

[12] Boverket, Miljö- och klimatanpassade byggregler, förstudie. (Environmentally and climate adapted building regulations, pre-study), Report 2016:14, Boverket, Karlskrona, Sweden, 2016.

[13] Embodied Carbon Industry Task Force Recommendations Proposals for Standardised Measurement Method and Recommendations for Zero Carbon Building Regulations and Allowable Solutions. http://asbp.org.uk/resource-report/embodied-carbon-industry-task-force-recommendations.

[14] Klima-, Energi- og Bygningsministeriet, Vejen til et styrket byggeri i Danmark – regeringens byggepolitiske strategi, rep. 2014/2015 : 04, Klima-, Energi- og Bygningsministeriet, Copenhagen, 2014.

[15] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, Hoofdstuk 5. Technische bouwvoorschriften uit het oogpunt van energiezuinigheid en milieu, nieuwbouw. http://vrom.bouwbesluit.com/Inhoud/docs/wet/bb2012/hfd5

[16] C-U. Chae, S. Kim, IEA-EBC Annex 57 Subtask2 report – A literature review, 2016. http://www.iea-ebc.org/projects/completed-projects/ebc-annex-57/

[17] R. Marsh, M. Lauring, E. Holleris Petersen, Arkitektur og Miljø: form, konstruktion, materialer - og miljøpåvirkning, Arkitektskolens förlag, Århus, Denmark, 2000.

[18] http://www.bauteilkatalog.ch/ch/de/Basisfunktionen.asp

[19] H. Birgisdóttir, A. Houlihan-Wiberg, T. Malmqvist, A. Moncaster, F. Nygaard Rasmussen, Evaluation of Embodied Energy and CO_{2eq} for Building Construction (Annex 57). Subtask 4: - Case studies demonstrating Embodied Energy and Embodied Greenhouse gas Emissions in buildings, Institute for Building environment and Energy conservation, Japan, 2016. Downloadable at http://www.iea-ebc.org/projects/completed-projects/ebc-annex-57/

[20] H. Birgisdóttir, A. Houlihan Wiberg, T. Malmqvist, A. Moncaster, M. Nehasilova, F. Rasmussen, E. Soulti, Evaluation of Embodied Energy and CO_{2eq} for Building Construction (Annex 57). Subtask 4:– Case studies and recommendations for the reduction of embodied energy and greenhouse gas emissions from buildings, Institute for Building environment and Energy conservation, Japan, 2016. Downloadable at http://www.iea-ebc.org/projects/completed-projects/ebc-annex-57/

[21] T. Malmqvist, H. Birgisdóttir, A. Houlihan Wiberg, A. Moncaster, V. John, A. Passer, E. Soulti, Design strategies for low embodied energy and greenhouse gases in buildings: analyses of the IEA Annex 57 case studies, World Sustain. Build. Conf. 2014 - Conf. Proc. (2014) 47–47.

[22] F. Nygaard Rasmussen, T. Malmqvist, A. Moncaster, A. Houlihan Wiberg, H. Birgisdottir, Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings, Energy & Buildings, 158 (2018) 1487-1498.

[23] A. Takano, S. Winter, M. Hughes, L. Linkosalmi, Comparison of life cycle assessment databases: A case study on building assessment. *Building and Environment,* 79 (2014) 20-30.

[24] S. Lasvaux, F. Achim, P. Garat, B. Peuportier, J. Chevalier, G. Habert, Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: What matters? Ecological Indicators 67 (2016) 174-182.

[25] N.W.O Brown, Basic Energy and Global Warming Potential Calculations at an Early Stage in the Development of Residential Properties, Proceedings of *Sustainability in Energy and Buildings, SEB'12, Springer,* Stockholm, Sweden, 2013.

[26] C. Liljenström, T. Malmqvist, M. Erlandsson, J. Freden, I. Adolfsson, G. Larsson, M. Brogren, Byggandets klimatpåverkan. Livscykelberäkning av klimatpåverkan och energianvändning för ett nyproducerat energieffektivt flerbostadshus i betong, Sveriges Byggindustrier, Stockholm, 2015.

[27] H. Darby, A.A Elmualim, F. Kelly. *A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building*. Sustainable Building Conference, SB13, 23-25 April 2013, Munich, Germany, 2013.

[28] J. Nakao, T. Malmqvist, M. Glaumann, Basic analysis to minimize contribution to climate change at building design - a Swedish case study, Integrated approach towards sustainable constructions, Department of Civil and Structural Engineering, University of Malta, 2011.

[29] J. Monahan, J.C. Powell, An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework, Energy and Buildings 43 (2011) 179-188.

[30] J. Salazar, J. Meil, Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J. Clean. Prod. 17 (2009) 156-171.

[31] B. Upton, R. Miner, M. Spinney, L.S Heath, The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass Bioenergy 32 (2008) 1-10.

[32] M. Wallhagen, M. Glaumann, T. Malmqvist, Basic building life cycle calculations to decrease contribution to climate change - case study on an office building in Sweden. *Building and Environment 46 (2011) 1863-1871.*

[33] L. Vukotic, R.A Fenner, K. Symons, Assessing embodied energy of building structural elements. Proceedings Of The Institution Of Civil Engineers Engineering Sustainability 164 (2010) 147-158.

[34] J. Růžička, F. Havlík, J. Richter, K. Staněk, K, Development of load bearing rammed earth wall panels – mechanical and environmental properties, influence to the indoor climate (sorption). In Zdravé domy. Brno, 2013.

[35] F. Havlík, J. Hodková, M. Nehasilová, J. Růžička, Environmental Characteristics of Rammed Earth, Czech Technical University in Prague, Unpublished, 2015.

[36] B. Sodagar, D. Rai, B. Jones, J., Wihan, R. Fieldson, The carbon-reduction potential of straw-bale housing, Building Research & Information 39 (2011) 51-65.

[37] B.V.V Reddy, Sustainable materials for low carbon buildings, International Journal of Low-Carbon Technologies 4 (2009) 175–181.

[38] H.Z. Cui, F.C Sham, T.Y Lo, H.T Lum, Appraisal of Alternative Building Materials for Reduction of CO2 Emissions by Case Modeling, Int. J. Environ. Res., 5 (2010) 93-100.

[39] N. Huberman, D. Pearlmutter, A life cycle energy analysis of building materials in the Negev desert. Energy and Buildings 40 (2008) 837–848.

[40] Korea Institute of Construction Technology, The study on GHG reduction and LCA on POSCO GREEN Building, RIST, 2012.

[41] K. Henson, Learning legacy: Lessons learned from the London 2012 Games construction project. London, 2011.

[42] P. Hájek, Kompozitní konstrukce na bázi vysokohodnotných silikátů a dřeva: environmentální optimalizace a experimentální ověření, GRADA, Prague, 2014.

[43] B. Lopez-Mesa, A. Pitarch, A. Tomas, T. Gallego, Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors, Building and Environment 44 (2009) 699–712.

[44] M.R. Inman, A.A-M. Houlihan Wiberg, Life Cycle GHG Emissions of Material Use in the Living Laboratory. In *CESB16 – Central Europe towards Sustainable Building, Grada, Prague, 2016*.

[45] T. Kristjansdottir, T.H. Dokka, B. Time, S, Mellegård, M. Haase, J. Tønnesen, J, *A zero emission concept analysis of an office building,* ZEB Project Report 8, SINTEF Academic Press, Oslo, Norway, 2013.

[46] T.H. Dokka, A.A-M.Houlihan Wiberg, S. Mellegård, I. Georges, B. Time, M. Haase, A.G. Lien, *A Zero Emission Concept Analysis of a Single Family House, Technical Report,* The Research Centre on Zero Emission Buildings (ZEB), NTNU, Trondheim, Norway, 2013.

[47] F. Rasmussen, H. Birgisdóttir, Livscyklusvurdering af MiniCO2-husene i Nyborg, Danish Building Research Institute, Aalborg University, Copenhagen, 2013.

[48] A. Rauf, R.H. Crawford, Building service life and its effect on the life cycle embodied energy of Buildings, Energy 79 (2015) 140-148.

[49] A. Grant, R. Ries, C. Kibert, Life Cycle Assessment and Service Life Prediction, Journal of Industrial Ecology 18 (2014) 187-200.

[50] E.B.P De Castro, M. Mequignon, L. Adolphe, P. Koptschitz, P, Impact of the lifespan of different external walls of buildings on greenhouse gas emissions under tropical climate conditions, Energy and Buildings 76 (2014) 228-237.

[51] K. Yokoyama, M. Yamamoto, Y. Noriyoshi, T. Oka, T. Sawachi, Study on impact of embodied energy and greenhouse gas emissions for prolongation of building life time: Case Study in Japan, Journal of Civil Engineering and Architecture 9 (2015) 274-282.

[52] F. Nygaard Rasmussen, H. Birgisdottir, M. Birkved, System and scenario choices in the life cycle choices of a building: changing impacts of the environmental profile, Proceedings of the Sustainable Buildings - Construction Products and Technologies, Verlag der Technischen Universität Graz, 2013.

[53] P.L. Gaspar, A.L. Santos, Embodied energy on refurbishment vs. demolition: a Southern Europe case study, Energy Build. 87 (2015) 386-394.

[54] C. Liljenström, T. Malmqvist, Resource use and greenhouse gas emissions of office fit-outs – a case study, *Conference Proceedings of Central Europe towards sustainable building, Prague, June 22-24, 2016.*

[55] H.M. Knight, How can sustainability be managed in design and construction to reduce the carbon footprint of buildings? Using the Olympic Delivery Authority as a case study, University of Cambridge, 2013.

[56] H. Hartman, London 2012 Sustainable Design. Delivering a games legacy, John Wiley & Sons, Chichester, UK, 2012.

[57] J. Quale, M.J. Eckelman, K.W. Williams, G. Sloditskie, J.B. Zimmerman, Construction matters. Comparing environmental impacts of building modular and conventional homes in the United States, Journal of Industrial Ecology 16 (2012) 243-253.

[58] S. Junnila, The environmental impact of an office building throughout its life cycle, PhD Thesis, Helsinki University of Technology, Helsinki, 2004.

[59] J. Tywoniak, M. Bureš, A. Lupíšek, M. Volf. New Generation of Curtain Walls, Proceedings of World Sustain. Build. Conf. 2014 - Conf. Proc. (2014) 1-7.

[60] P. Melià, G. Ruggieri, S. Sabbadini, G. Dotelli. Environmental impacts of natural and conventional building materials: A case study on earth plasters, Journal of Cleaner Production 80 (2014) 179–186.

[61] T. Pavlů, Use of recycled aggregate for concrete structures, PhD Thesis, Czech Technical University in Prague, 2015.

[62] M. Tyrer, C.R Cheeseman, R. Greaves et al. Potential for carbon dioxide reduction from cement industry through increased use of industrial pozzolans, Advances in Applied Ceramics 109 (2010) 275–279.

[63] K.H. Pedersen, A.D. Jensen, M.S Skjøth-Rasmussen, K. Dam-Johansen, A review of the interference of carbon containing fly ash with air entrainment in concrete, Progress in Energy and Combustion Science 34 (2008) 135–154.

[64] B. O'Rourke, C. McNally, M.G Richardson, Development of calcium sulphate –GGBS – Portland cement binders, Construction and Building Materials 23 (2009) 340–346.

[65] T. Garcia-Segura, V. Yepes, J. Alcala, Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int. J. Life Cycle Assess. 19 (2014) 3-12.

[66] RiBuilT, The district of tomorrow. Retrieved from http://www.sustainablebuilding.info/districtoftomorrow/

[67] Labs HI Research, Home > Design & Construction Guides >Foundations [Internet]. http://www.toolbase.org/Design-Construction-Guides/Foundations/concrete-alternatives

[68] R.J. Cole, P.C. Kernan, Life-cycle energy use in office buildings, Building and Environment, 31 (1996) 307-317.

[69] N. Howard, H. Sutcliffe, Precious joules, Building (1994) 48-50.

[70] G.J. Treloar, M. McCoubrie, P.E.D. Love, U. Iyer-Raniga, Embodied energy analysis of fixtures, fittings and furniture in office buildings, Facilities 17 (1999) 403-409.

[71] D. Kellenberger, H.-J. Althaus, Relevance of simplifications in LCA of building components, Build. Environ. 44 (2009) 818–825.

[72] Iron and Steel Institute, World Steel Life Cycle Inventory – Methodology Report 1999–2000, IISI Committee on Environmental Affairs, Brussels, 2002.

[73] P. Russell, S. Moffatt, Assessing buildings for adaptability, Background report, Annex 31 – Energy-Related Environmental Impact of Buildings, Canada Mortgage and Housing Corporation, 2004.

[74] J. Wangel, M. Wallhagen, T. Malmqvist, G. Finnveden, Cerfification systems for sustainable neighbourhoods: What do they really certify? *Environmental Impact Assessment Re*view *56 (2016) 200–213.*