Energy in Buildings and
Communities Programme

International Energy Agency

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 embodied greenhouse gas emissions from buildings

November 2016

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Czech Republic
Denmark
Finland
Germany
Japan
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Sweden
The Netherlands
United Kingdom

Observer country:
Brazil

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International Energy Agency

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Subtask 4: Case studies and recommendations for the reduction of embodied energy and embodied greenhouse gas emissions from buildings

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)

Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior Simulation
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Executive summary

This report describes the research conducted by Subtask 4 (ST4) of IEA EBC Annex 57 of the International Energy Agency implementing agreement. The ST4 task was to identify and define measures to design and construct buildings with lower embodied energy and greenhouse gas emissions (EEG). In order to do this, ST4 collected and analysed around 80 case studies from the wider IEA EBC Annex 57 group. These have been collated using a template format designed by ST4 to enable transparency and accurate comparisons between cases. The full collection of the completed case study templates is included in the accompanying **IEA EBC Annex 57 report** on Case studies demonstrating Embodied Energy and Embodied Greenhouse gas Emissions in buildings. Supplementary data was collected through surveys and discussions within the Annex 57, and through discrete literature reviews. Four different levels of analysis were used to assess the impacts of methodology on the numerical results, the range and average values for impacts of different life cycle stages, components and building typologies, potential design and construction strategies for reducing EEG, and the influence of decision-making contexts on measuring and reducing EEG in buildings. Each theme is summarized below.

Impact of methodology on numerical results

Any analyses of LCA studies should start with a detailed understanding of the methodology used, as this can have a considerable impact on the results. The first ST4 analysis identified a number of methodological impacts on the case study results. Such differences include the system boundaries – both chronological (the life cycle stages included) and physical (the completeness of the inventory), the assumed future scenarios such as for service life of materials and end-of-life treatments, the reference study period, and the LCA method used – process, input-output and hybrid approaches. These were all represented in the collected case studies. This analysis illustrates the importance of a transparent declaration of methods, system boundaries and data in building LCA studies; it is proposed therefore that the use of the ST4 template for reporting dissimilar case studies as well as the minimum data requirements proposed by Annex 57 ST1, should be adopted by academics and practitioners.

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, in studies using similar methodological approaches. 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 EEG for new buildings. For refurbishment cases it was found, however, that the replacement stage (module B4) can contribute almost the same as the production stage. Technical services equipment can be responsible for a high part of the whole life EEG, although it is also frequently excluded from assessments perhaps due to a lack of data. The materials contributing the highest impacts are concrete and metals, particularly since concrete is often used in large amounts, for example in foundations. The cases which compare timber with concrete or steel demonstrate that timber is a lower EEG solution whether carbon sequestration is taken into account or not.

Strategies for the reduction of EEG in buildings

The third analysis builds upon the insights of the previous two themes to develop reduction strategies, which are discussed in chapter 4 under the following three main categories; substitution of materials, reduction of resource use and reduction of construction and end-of-life stage impacts. For the first category, a number of the case studies demonstrate that the substitution to bio-based materials will reduce EEG, due to the low-energy production methods. However the analysis of studies of recycled or innovative materials is inconclusive. The reduced use of materials, through for instance, the use of light-weight construction and reuse of old building structures, are found to be effective reduction strategies measures. The

analysis also revealed that only limited studies exist which examine the impact of other strategies such as design for flexibility, adaptability and reuse. Other strategies include consideration of service life extension. This is likely to decrease EEG, although more durable components may have a higher initial impact, it is likely that the investment in more durable components considerably lowers the total impacts than more frequent replacements; however each building should be assessed on the context and probable service life. Finally, while the construction stage modules A4-A5 typically contribute a smaller share of the total EEG, choices such as the energy-carrier, energy efficiency on site, site waste management, and seasonal timing of construction, can all reduce EEG.

Decision-making contexts for EEG

The final theme discusses both the intentional and unintentional impacts on EEG reduction of national and project contexts. At a national level, there is little current regulation to reduce EEG from buildings. However a wide number of certification schemes, databases and tools have been developed. Environmental Product Declarations (EPDs) are also becoming more common, although numbers vary significantly country to country and they currently lack conformity. While regulation is seen as a key factor for the reduction of EEG, and one which Governments should be encouraged to implement, the important role of bottom-up initiatives by individual organisations or groups of construction firms has also been demonstrated, repeatedly and across different countries. Tools, databases and certification schemes are shown as both useful but also potentially limiting, through their lack of data on innovative or small-scale materials. The provision of data on innovative and low EG materials needs to be supported at a national level in order to be accessible to small and medium-sized construction projects.

Final remarks

A key challenge of LCA calculations is that they can be used to produce figures for EEG, which may be misused and misinterpreted by politicians and other decision-makers. However, as can be seen in the depth analysis produced in this report, it is clearly demonstrated that there is diversity in results which may lead to a misleading assumption that a singular methods is fundamentally flawed. To the contrary, this report has also demonstrated that as LCA methodology is becoming adopted more frequently and consistently, there are important and meaningful conclusions and recommendations that can be drawn. The potential to significantly reduce the EEG from buildings, through a wide range of different measures, has been clearly demonstrated.

The use of the case study template was, to our knowledge, a unique approach to analysing diverse data from a wide number of academic participants. The intention was never the direct comparison of results nor an attempt to develop one standard LCA method but rather to create to transparency in the different parameters that impact the final results. The collection of the case studies, and their careful analysis through four different approaches, has produced an important body of work. This will push forward the understanding both of the extent of embodied impacts of buildings, and of the methods by which we can reduce them.

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Foreword

The interest in issues related to the determination, assessment and influencing of embodied energy and embodied greenhouse gas emissions of construction products and buildings has grown significantly during the last years. Although the fundamentals in the form of terms, system boundaries, data bases and calculation rules have already been, to some extent, a subject of scientific discussion and international standardization, they are not yet in a form that facilitates their application and leads to clear and transparent results. This is where the contribution of IEA EBC Annex 57 comes in; it presents the fundamentals in such a way that they can be efficiently included in the decision-making of relevant actors. The overall work is accomplished through the different subtasks (STs):

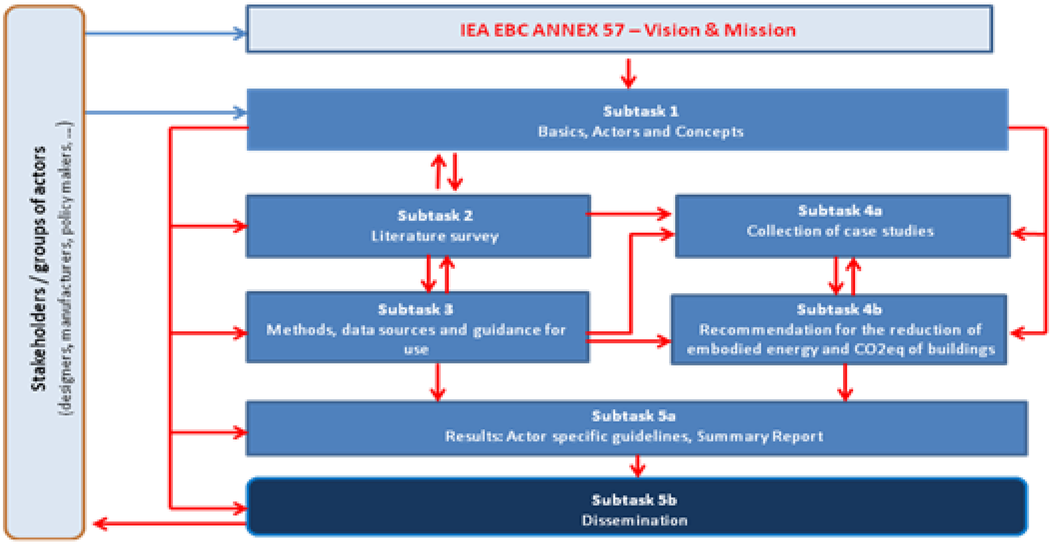
ST2 analyses the status of the scientific discussion on the basis of an evaluation of available literature. The identified misconceptions and gaps form the basis for the Annex 57 work.

ST1 picks up on the results of ST2 and develops recommendations for indicators and system boundaries to ensure transparent and accountable results and allow for the classification of existing approaches in a unified system. Additionally, it explains how to describe the building and its life cycle and the data needs for calculations at the building level. Finally, it presents the relevant stakeholder groups and decision-making situations, including recommendations for action.

ST3 deals with issues related to the development and provision of data. Specifically, it describes specific methods for developing data for embodied energy and emissions and analyses available databases, while classifying them in an overall system.

ST4 deals with the collection, presentation, evaluation and classification of case studies using a typology developed on the basis of partial results of the other STs. As a result, design recommendations for achieving buildings with low embodied energy and GHG emissions are derived from the analysis of the extensive collection of case studies taking into account their interaction with the other design objectives and criteria.

ST5 presents the results in a way to appeal to politicians, scientists and practitioners. In this context, actor specific guidelines were developed that can be found available at the Annex 57 homepage. The interrelationships between STs are illustrated below:



Subtask 4 of IEA EBC Annex 57

The purpose of Subtask 4 (ST4) has been to collect relevant building case studies and use these to develop measures to design and construct buildings with less embodied energy and greenhouse gas emissions. This report is the final output from the Subtask work. It explains the work of ST4, analyses the case studies collected from Annex 57 members, and discusses approaches to reducing embodied energy (EE) and embodied greenhouse gas emissions (EG) from buildings. In addition, all Annex 57 case studies are compiled in an independent report: IEA EBC Annex 57 ST4 Case study collection report. The ST4 group has also produced a Guideline for designers with recommendations for reduction of embodied energy and greenhouse gas emissions based on the analysis developed in the current report, Guideline for designers and consultants – Part 2.

1 Introduction

1.1 Embodied energy and greenhouse gas emissions

The built environment has been long recognised as the major emitter of greenhouse gases. Regulations to reduce energy use and greenhouse gas emissions from buildings, for example by the EU through the Energy Performance of Buildings Directive (EPBD) 2002 and subsequent recasts have focused on *operational* impacts. These are the impacts from the energy used in buildings, including lighting, heating and ventilation. Research into reducing operational energy and greenhouse gas emissions has encouraged technical design changes to buildings, more recently also considering the impacts of occupier lifestyle and behaviour, and has started to incorporate the emissions resulting from electronics and white goods. However the energy used in, and greenhouse gas emissions from, manufacturing the construction materials, and constructing, maintaining, refurbishing and demolishing the buildings – the *embodied* energy and greenhouse gas emissions (EEG) - are not included in most regulations or design changes. While these impacts have been considered at a sector-wide scale, regulations to reduce the embodied impacts of buildings have been limited or non-existent and reductions have therefore been marginal or even negative (see for example GIG and WRAP, 2014).

The European Technical Committee CEN/TC 350 has developed a suite of standards on the Sustainability of Construction Works, including key standards EN 15978: 2011 and EN 15804:2012. The modular setup of the building life cycle model described in the CEN/TC 350 standards is previously introduced in the International ISO 21931-1:2010. These international and European standards therefore encourage consideration of the embodied impacts alongside the operational impacts, at a building level, and although not yet mandatory, have resulted in an increase in interest in calculating and reducing the EEG of buildings.

The standards define four life cycle stages of construction products or buildings (see figure 1): ‘product’ (impacts from materials extraction, transport to factory, manufacture and processing), ‘construction’ (impacts from transport of materials to site and the construction process), ‘use’ (impacts from e.g. maintenance, replacement of components and refurbishment of buildings – this stage also includes the operational components), and ‘end of life’ (impacts from demolition processes, transport and processing of waste). They also define a fifth stage as ‘beyond the building life cycle’, which includes positive benefits such as from recycling and reuse of components.

	Life cycle stage	**Module**	
Building life cycle information	Product stage	A1	Raw material supply
		A2	Transport
		A3	Manufacturing
	Construction process stage	A4	Transport
		A5	Construction, installation process
	Use stage	B1	Use
		B2	Maintenance
		B3	Repair
		B4	Replacement
		B5	Refurbishment
		B6	Operational energy use
		B7	Operational water use
	End of life stage	C1	Deconstruction, demolition
		C2	Transport
		C3	Waste processing
		C4	Disposal
Supplementary information	Benefits and loads beyond the system boundary	D	Reuse-, recovery-, and/or recycling potentials

Figure 1. Building assessment information as described the CEN/TC 350 standards

1.2 Research design

1.2.1 *The use of case studies*

The calculation of EEG of buildings is a mathematical exercise which can be undertaken for individual components or for whole buildings. However there are inherent complexities in the calculation for whole buildings, due to the calculation method, the difficulties of assessing future impacts, problems with identifying system boundaries, limited available data, and the wide variation in building materials, typologies and design approaches. The **IEA EBC Annex 57, ST1 report** attempts to address many of these issues for those embarking on the calculation of full embodied impacts for a building through a series of recommendations for approaches to system boundaries, and checklists to demonstrate where only partial system boundaries have been used.

In contrast, the focus of this report is to discuss the issues faced in practice by designers and policy makers. It is based on a series of around 80 case studies conducted by, or with input from, the contributing authors, and by other members of the wider Annex 57 and their contacts. The case studies analysed in this report are representative of the information on EEG currently available both in emerging academic publications and within different national contexts. Further information on the method used to produce the studies is given in the following sections.

The use of case studies in this context – usually the analysis of a particular new building, or more occasionally of a major refurbishment project – is the most common approach used to demonstrate EEG. Results are usually published in academic dissertations and peer-reviewed papers, and are often then used by policy makers to identify the extent of embodied impacts.

However, very few current case studies follow the internationally standardised recommendations for full analysis now clarified in the **IEA EBC Annex 57, ST1 report**, and even fewer are likely to be based on full and accurate input data for materials and components. There is also a huge variation in construction methods and building types and designs, both within and across different geographical regions and cultures. One of the issues therefore highlighted by this report is the fact that each case study is developed within a particular context and to illustrate a particular issue; the use of the data from a single case will never be sufficient to identify the embodied impacts of building in general, and even data from a series of cases will only be of general application if considered within the original purpose of the studies. The report and the results published herein should be read with this in mind.

1.2.2 *Preparation of case study template*

Analysis of, and comparison between, multiple case studies from different sources is also difficult because of the lack of transparency and completeness of data. The purpose of this collection of case studies was to produce a body of different studies, carried out in different countries and for different purposes, for which the relevant data was easily accessible and identifiable. These could then be used to compare between studies for specific aspects. The initial preparatory work was the development of a template through which case studies could be submitted. The template was designed to allow the widest variety of studies – including qualitative studies – while encouraging transparency and completeness of quantitative data.

The template was designed during the first year of the IEA EBC Annex 57 project. As well as providing a quantitative checklist, which shows the life cycle boundaries and the source of data, the template asked for the incorporation, where possible, of the aspects of interest identified in the early meetings of the full team. These aspects included:

- The original objective of the case study.

- The identification of the potential stakeholders who might find the case studies of interest – the Annex 57 team identified a number of these :
    - National government/policy
    - Local government/planning
    - Designers/consultants
    - Developers/contractors
    - Clients/owners
    - Manufacturers
- The identification of the 'theme' of the case study - these too were developed through discussions with the Annex 57 participants, and were initially intended to be the divisions for the analysis:
    - Strategies for reduced EEG
    - Significance of different factors over the full life cycle
    - Impacts of calculation method and system boundaries
    - Reduction strategies, significant factors and calculation of EEG for building components and building materials
    - Reduction strategies, significant factors and calculation of EEG for building sector at national level
    - Integration of EEG calculations in decision making process.

Contributors of the case studies were also asked to provide information about the country of production and the type of building, and to provide references where possible to published sources for background data.

1.2.3 *Collection of case studies*

The IEA EBC Annex 57 participants were asked to submit case studies in 2013, again in 2014, and finally in 2015. The studies are based on detailed reports or published academic literature. ST4 asked that the studies be submitted using the prepared template, thus ensuring that comparable data was provided where possible, and that the raw data or public academic literature and reports were also made available to the report authors, and were referenced within each case study description.

Around 80 case studies were collected through this method from across the countries represented within IEA EBC Annex 57. The ST4 members numbered the cases in sequential order in which they were received, with a suffix identifying the country of origin. Authors of the case studies retain full responsibility for the content: however where obvious mistakes were made in the preparation of the template (for instance where a template had been copied from the example with the original country still identified) these have been corrected by ST4.

Malmqvist et al (2014) describes the methodology through which the cases were identified and categorised. The full collection of case studies is available in the separate **IEA EBC Annex 57, ST4 Case study collection report**. Within this compiled report, a more thorough description and thematic listing of case studies is provided.

1.2.4 *Supplementary data: cases from the literature and questionnaire*

The authors of each chapter of the report also carried out supplementary literature reviews in order to identify published case studies and information which related to the chapters. These are referenced at the end of the report.

To supplement the case studies on national contexts, in April 2015 all IEA EBC Annex 57 members were asked to answer a questionnaire on the status of EEG within their country. The questionnaire was presented at the Annex meeting in Venice and responses were collected from 16 countries. The results are reported in chapter 5.

1.2.5 *Analysis*

The case studies were analysed during the final year of the project by the ST4 members. Additional information where needed was identified as described in the previous section . Four specific areas for analysis were developed during the course of the project, and are described in the next section and in the following four chapters. Each analysis area was the responsibility of two or three members of the ST4 group, with one retaining the role of principal editor for that area. The individual case studies used within the analysis are listed within each chapter.

1.3 Structure of this report

The report offers four analytical perspectives, addressed in the following four chapters.

Chapter 2 considers the impacts of methodological issues on the results obtained and the conclusions drawn, using single case studies as examples. Chapter 3 presents and reviews the results of multiple case studies to compare the impacts from different life cycle stages, materials and components. Both chapters therefore have a role in explaining how different case studies can be used in analysis.

Chapter 4 then uses the results of the case studies, in the light of the insights from the previous two chapters, to consider design and construction strategies which can be used to reduce embodied energy and greenhouse gas emissions from buildings.

Chapter 5 discusses the influence of context, such as regulation at national level or the use of design tools at project level, on the measurement and reduction of the embodied impacts.

The final chapter 6 provides a summary of the results from the four analysis chapters, and presents a series of recommendations.

2 Impacts of calculation and system set-up

2.1 Introduction

The uniqueness of constructed buildings makes direct comparisons of LCA results difficult. In figure 2, cradle-to-gate EG results from a selection of the IEA EBC Annex 57 case studies are shown which represents the wide diversity of the results from all the case studies. This diversity can, to some degree, be explained by further examination of the background of the different case studies, where one finds that methodological choices and system set-up is applied differently from case study to case study and from country to country. For instance, the goal, scope and methodology of the case studies are different, some are simplified inventory for early design choices (such as **SE2a**) while some are performed at a very detailed level of inventory when a building has been built (such as **NO4**). Some studies (such as **AT5**) accounts for carbon storage in wood, hence "neutralising" the greenhouse gas emissions from production of other building components. Some studies (such as **DE4**) show the relatively large impacts associated with technical equipment, but still manage to present the total results of the cradle to gate EG that are within the same range as studies with a limited inclusion of technical equipment (such as **DK3c**). Input-Output based LCA (as in **JP5**) is used in some studies although most Annex 57 case studies are process based. A range of case studies present results for refurbished buildings (such as **CH1**) and a few studies include different methodological aspects of recycled materials used in the construction of a new building (such as **KR3**). Even within the same country different system set-up is used (for instance seen in **AT5** and **AT6**) and thus produces results that are difficult to compare. Furthermore, it should be noted that the performance indicator displayed in figure 2 is kg CO_{2eq}/m^2. Furthermore, some of the case study calculations are based on gross floor area whilst others are on net floor area which can make a difference of at least 10% of the area being used.

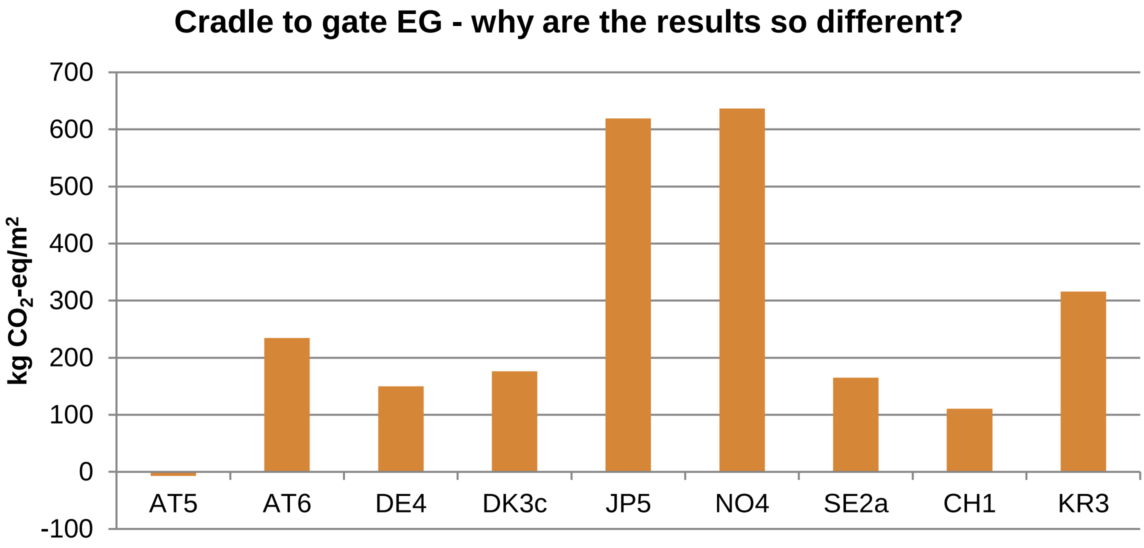


Figure 2. Embodied GHG emissions from the cradle to gate stage of different Annex 57 case studies. See appendix I for the list of case studies included in the IEA EBC Annex 57 work.

This chapter focuses on the impact of calculation methods and system boundaries applied in the Annex 57 building LCA case studies. The analyses made in this chapter consider the impact of different methodological choices of system set-up on the case study results. Examples of important methodological choices in relation to EEG include length of the reference study period, completeness, choice and source of building data, as well as scenarios defined for the building life cycle. All available results of EEG from the case studies are presented in chapter 3.

2.2 CEN/TC 350 as a framework for analysis

The European Committee for Standardisation Technical Committee 350 (CEN/TC 350) has developed a set of standards for the assessment of the environmental performance of buildings. These standards are based on the LCA standards ISO 14040/14044 in terms of methodology and on the ISO 21931-1:2010 in terms of modularity principle of the building life cycle. The standards thus provide a system framework tailored for the purpose of building LCAs.

The analysis in this chapter looks into the study of specific parameters from the system and calculation set-up in accordance with the 8 methodological steps from EN 15978 illustrated in table 1 below. The analysis contains descriptions of the different approaches within each information module outlined in EN 15978. The different approaches are then illustrated with examples from the Annex 57 case studies or from peer reviewed studies in scientific journals.

Table 1: Methodological proces steps for assessment from EN 15978 and identified themes analysed.

Process steps for assessment (according to EN 15978)	Identified themes (based on the Annex 57 case studies)	Exemplifying Annex 57 case studies
Identify purpose of assessment	Purpose of study	CH1-CH13 SE2a, SE2b, SE5 UK2, UK7
Specification of the object of assessment	Functional equivalent of study	-
	Reference study period	DK3a, DK3b JP4, JP6 NO4
	System boundaries	DK2
	Building model - physical characteristics	(See chapter 4)
Scenarios for the building life cycle	Scenarios - time and space related characteristics	-
	Scenarios for life cycle stages	DK1, DK3 JP5 NO1, NO2, NO4, NO8, NO9 SE6 UK9
Quantification of the building and its life cycle	Building inventory	JP6 NO1, NO2, NO4
Selection of environmental data and other information	Background data	AT1-AT3, AT5 NO1, NO4
Calculation of the environmental indicators	Indicators and reference units	-
Reporting and communication	Performance indicator	NO4
Verification	[not relevant in current project]	-

The standards are developed in a European context and furthermore, are recently published in 2011. Hence, it is not surprising if many of the published building LCA case studies used for this analysis do not follow the EN 15978 explicitly. This adds an additional element of interpretation in some case studies, in particular, about the terms used in studies to express the different life cycle stages.

2.3 Purpose of study

The goal and intended use definitions are the first steps of a LCA according to the international ISO 14040-series, as well as the European CEN/TC 350 standards. The goal and intended use are thus the first scene-setting decisions taken for a LCA study. A variety of reasons can drive the motivation for conducting a LCA study of a building, for instance, a need for comparing different structures in terms of their environmental performance, identification of environmental impact hot-spots in the construction, or simply to document the environmental performance. The goal and intended use of the study are thus important to the eventual building LCA results because subsequent decisions about functional unit, scope and other parameters are aligned with the defined goal.

Examples from the Annex 57 case studies

In case study **UK7**, a comparison is conducted between a building structure of wood with that of steel. The goal of the study is to facilitate a comparison of the differences between the two scenarios. All materials considered equal in the two scenarios are left out of the assessment. Thus, the impact assessment results are representative of a limited material inventory, yet the LCA is fit for the purpose of comparison of these two structural materials.

In the Swedish **SE2a**, **SE2b** and **SE5** case studies, the results reflect how the objectives of the studies assist in decision making in the early design stage. Thus, LCA's are performed primarily to identify the design possibilities that have the greatest potential to have an environmental impact and typically, only the main building elements are included in the calculations at this stage. For comparisons within a specific project at this early stage, this type of analysis may be sufficient. However, results should not be compared with studies carried out on the basis of other objectives or those conducted at a later design or as-built stage when the material inventory is much more comprehensive.

In the reported Swiss case studies (**CH1-CH13**), direct comparison between the case study buildings is exactly the objective of the studies, such that all the studies are consistent in scope, level of detail, use of database and other parameters.

An additional type of objective might be to evaluate environmental pay-back times. This is particularly important for building renovation studies where the impacts from the production stage are compared with the resulting savings in the operational energy used in the building. In the **UK2** study, a renovation of four different residential buildings, the energy and carbon pay-back time from the production of materials was calculated to be between 6 and 33 months.

2.4 Functional equivalent of study

The functional equivalent of the building LCA study essentially describes the provided service of the product system. This service is determined by building typology, pattern of use and the required service life, which are all parameters affecting design options and hence, the use of materials. Functional and technical requirements are also important. For instance, a building with a technical requirement of low energy consumption in the use stage will most likely involve the increased use of insulation material, and hence associated increase in EG, compared with a regular building of same construction. The comparison of embodied impacts of two buildings which differ in technical requirements related to the u-values of construction is thus not a fair comparison. In addition, the operational energy needs to be taken into account in order to create a comprehensive picture of the building's actual environmental impact. Other technical requirements should also be included, such as those required to achieve certain standards of fire safety.

Functional requirements of a building can also be related to the building typology, for example, whether the building is an office or a factory and how this affects the pattern of use for the specific building.

2.5 Reference study period

The length of reference study period (RSP) is an important factor for the calculation of results. The choice of RSP can be viewed from two perspectives, namely:

- As a numerical exercise for calculating annualised impacts, an often preferred way to report results of a building LCA (see also section 2.13)
- As a parameter reflecting the actual design, where solutions for extension or limitation of the building's service life is sought after (see also chapter 4)

Examples from the Annex 57 case studies

An example of the numerical perspective can be found in case study **NO4** where results of the cradle to site (modules A1-A4) are calculated for different reference study periods: the results with RSP of 120 years were found to be 11.8 kgCO_2-eq/m^2/year, whereas a RSP of 60 years gave 23.6 kg CO_2-eq/m^2/year and RSP of 30 years gave 47.2 kg CO_2-eq/m^2/year. The results show that the longer the reference study period, the more years available to distribute the emissions, leading to lower reported emissions on an annual basis. Thus, a doubling in RSP leads to a halving of reported annualised emissions and vice versa. However, this of course is a mathematical exercise and there has been no change in the design or choice of the materials in accordance with a longer or shorter RSP. Furthermore, had the assessment included processes from the use stage (e.g. replacements – module B4), a longer RSP naturally adds embodied impacts from these extra materials. The mathematics when including use stage processes is thus not quite as straight-forward as halving annualised results when doubling RSP because the results will depend on the scenarios defined for the buildings' use stage (see section 2.9.3).

The other approach is one where the design or choice of material has been modified with a view to increasing the building lifetime or for a building designed with a short lifetime, such as a temporary structure. This can be demonstrated in the two Japanese case studies **JP4** and **JP6** where cradle to gate (for **JP4**) and cradle-to-site (for **JP6**) are calculated. In order to increase the building life time from 50 or 60 years to 100 years, the covering thickness of concrete, the steel frames and oil dumpers are redesigned to increase earth-quake resistance strength. Likewise in the Danish case study **DK3a-b** where the buildings are designed with large roof overhangs to protect vulnerable building components such as windows, thereby increasing the service life of the components. Design measures like the ones mentioned will naturally affect the calculated embodied impacts from the building.

2.6 System boundaries

2.6.1 *Process modules included*

An important factor which affects the total results of a building LCA, is the selection of which life cycle stage processes to include in the LCA. Most recommendations and standards on building LCA suggest full inclusion of all life cycle stage processes, but this is rarely, if ever, actually conducted. Sometimes, the simplifications are justified in accordance with the goal and scope of the study and follow the usual system boundary types such as cradle to gate, cradle to site, and cradle to grave. (see more about these types in the **IEA EBC Annex 57, ST1 report**). The stage of design, such as in the early phase, can also be a reason to simplify the assessment, for instance when there are many uncertainties, limited material inventory and lack of sufficient background data.

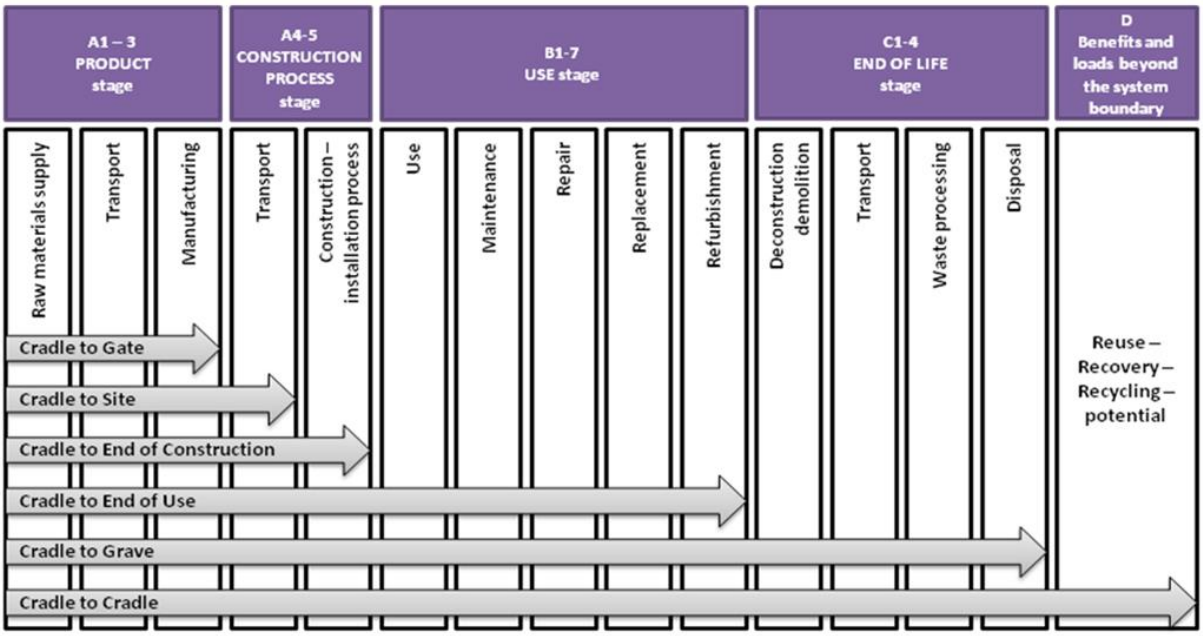


Figure 3. Overview of the various existing system boundary types using the respective modules of the building life cycle model. Figure from IEA EBC Annex 57, ST 1 report .

The more modules included in a building LCA, the higher level of comprehensiveness and thus higher quantified levels of the resulting EEG. Therefore, a comparison of total results from different case studies which include different selections of modules is therefore not advisable. In addition, even though the same system boundary type (figure 3) is used, the comparison of results between different studies is difficult due to all the other parameters influencing results, unless of course, there is full transparency and comparisons can be made where like is compared to like. This can be seen in the cradle to gate results from the Annex 57 case studies as illustrated in figure 2.

By far, most reported Annex 57 case studies include selections of modules across the five life cycle stages as shown in the summary presented in Appendix I.

In chapter 3, the results from the process modules of the different Annex 57 case studies are analysed to examine the relative contributions from the included life cycle stages.

2.6.2 *Allocation of impacts*

Following the ISO standards, the allocation of impacts in co-production situations shall be avoided. In practice however, most building LCAs rely on attributional data based on allocation procedures and choices which become an inherent part of the system. This is dealt with in more detail in the **IEA EBC Annex 57 ST 3 report**.

Example from the Annex 57 case studies

In some cases, the allocation becomes an issue when performing a building LCA. This is, for instance, the situation in case study **DK2** where the building uses various recycled materials as part of the construction. The recycled materials can be regarded as by-products of a waste treatment service from an upstream process. This raises the question of how much of the environmental impacts, compared to a newly produced material, should then be accounted for? In this case study, an economic allocation is performed to account for environmental impacts according to the price ratio between recycled and new materials. However, there are many ways this allocation of impacts could be done, and when the allocation key is as determining for the results, as in the case of **DK2**, results should preferably be tested with other allocation approaches.

2.7 Building model – physical characteristics

Physical characteristics of the building are important, in so far as the choice of material used in the construction as well as operational conditions are dependent on the design. This influence of the building's physical characteristics is further presented in chapter 4, where they are analysed in several building case studies on the basis of their potential as design strategies to reduce EEG.

2.8 Scenarios – time and space related characteristics

Time and space related characteristics influence the building design and operation such that the building is designed for a specific standard that varies in time and space. For example, thermally comfortable buildings in colder regions necessitate higher levels of insulation, or higher energy use for heating than would be the case for buildings in warmer regions where cooling may be a pre-requisite. Thus, the climatic scenarios must be defined to properly describe the characteristics of each building study.

Temporal aspects also apply for instance to all periodic operations in the building's operation stage such as cleaning and replacement. This is further elaborated on and exemplified in the following section 2.9.

2.9 Scenarios for life cycle stages

2.9.1 *Scenarios for the product stage (modules A1-A3)*

Scenarios for the product stage relates to the extraction and manufacturing processes as well as the related transport. For process based building LCA's following the EN 15978 approach, the scenarios for the production stage are defined in environmental product declarations (EPD's). The significance of different scenario choices is thus optimally assessed on a single material level rather than on a building level.

2.9.2 *Scenarios for the construction stage (modules A4-A5)*

Even though some Annex 57 case studies do include impacts from transport to site and construction activities, none of the case studies, look into the influence of different scenarios for transport and construction. The results from a case study by Kellenberger and Althaus (2009) which shows the EEG for the 'cradle-to-end-of-construction' (modules A1-A5) stages for five different wall components', found that the construction process of the components accounts for less than 8 % of the total results regardless of the type of component. However, the study furthermore concludes that transport related impacts vary a lot between the different types of wall components and should therefore not be ignored.

2.9.3 *Scenarios for the use stage (modules B1-B5)*

The use stage of a building life cycle covers an extensive period of time, which in the Annex 57 case studies was found to be usually 50 years or more. Obviously, this is a long period to account for in terms of scenario building and the related uncertainties about the chosen scenarios thus become more prominent. Modules affecting the EEG are limited to B1-B5 since operational energy use (B6) and operational water use (B7) are outside the scope when it comes to accounting of embodied impacts of a building.

Use (module B1)

Although a number of the Annex 57 case studies report the inclusion of this process module, actual results or assessments of the module are, except for the **JP5** case study, absent. The term “Use” in the CEN/TC 350 standards for describing the overall life cycle stage *and* the process module may easily cause confusion about the actual content of the process module. This ambiguity could mean that the B1 module concept is misunderstood, and thus in practice, not included nor reported in the case studies.

Despite this, what is included in the module according to the CEN/TC 350 standards, are scenarios for humidity, air velocity and temperature which determine the release of substances into the surrounding environment. For the IEA EBC Annex 57 work, this is specifically relevant for materials which emit or bind GHGs in the use stage. Examples of this could include the release of GHGs from plastic blower agents in insulation or the uptake of CO_2 from the carbonisation process in cement and concrete. For some building products/processes, it may be difficult to determine whether these emissions should be attributed to the A3, the A5 or the B1 module. The **IEA EBC Annex 57 ST1 report** elaborates on this aspect of determining and reporting emissions in a transparent but separate manner.

Example from the Annex 57 case studies

The Japanese IO case study, **JP5**, investigates the EG of an office building and the significance of Freon gasses included as contributors to the EG. The results show that use stage emissions of freons from insulation materials and refrigerants contribute with 2 % and 10 % respectively of the building’s embodied GHG emissions from the life cycle stages included; cradle to end of construction, repair, replacement, refurbishment and demolition. Note that the Freon gas emissions from the refrigerants are in this specific case study not reported as occurring within the B1 module although the IEA EBC Annex 57, ST1 report recommends it for this type of emission source.

Maintenance, repair, replacement, refurbishment (modules B2-B5)

The scenarios for the B2-B5 modules describe how materials, components or even the building itself is maintained, repaired, replaced and refurbished. The underlying factors determining the impact on results of these scenarios can be narrowed down to:

- The scale of intervention)
- The frequency of intervention)

Examples from the Annex 57 case studies

The replacement module (B4) is the single most included module from the use stage in the Annex 57 case studies. The longer the reference study period (RSP), the more significance the replacements will have on the total results. This can be observed in case study **DK1** where RSPs of 50 and 100 years are evaluated on the same building. This prolongation changes the EG contribution from the replacement stage from 11% to 28% of the production and replacement total results (i.e. A1-A3+B4). For the EE, contribution from the replacement stage changes from 17% to 39% of the production and replacement total results. Note that a doubling of the RSP results in more than a doubling of the relative contribution of replacements to the results. This is due to the required service life (RSL) scenarios defined for the individual materials/components, where it was found that after a period of 50 years some significant replacements takes place, for instance in the outer wall cladding which results in an increase in EEG.

In the Norwegian case studies **NO1, NO2, NO4, NO8 and NO9**, the divergence in RSL of certain products was found to be significant. These differences arise since often times, there may be no information given in the LCA or EPD databases for certain materials. In these absences of RSL data, the researcher might have no choice but to use manufacturer's literature which may result in different RSL being used in the various case studies. For example, **NO1** and **NO2** use 15 years for wooden flooring, whereas **NO9** uses 20 years and the manufacturer's literature claims an RSL of 25 years. Another example includes the hot water tank which for **NO1** and **NO2** is declared using 30 years as RSL, whereas **NO9** uses 60 years. The Sintef Byggforsk literature gives a 10 year RSL for copper/steel hot water tank and 20 years for a stainless steel type. The ongoing harmonisation work within the Norwegian ZEB pilot project case studies is to document these differences and come to a consensus on the recommended RSL for different products and materials.

In figure 4, results from an on-going building LCA of an eight-storey multifamily building in wood in Sweden, are displayed (Larsson, M et al, 2016). The contribution to GWP for all modules besides B4, replacement, is fixed.

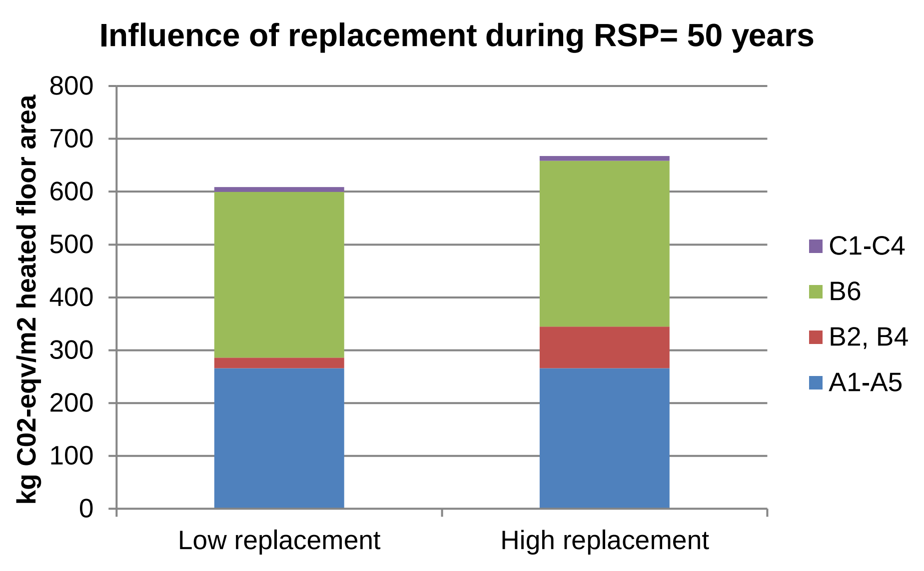


Figure 4. Embodied GHG emissions at different scenarios for required service life of materials.

Based on data for lowest and highest replacement and maintenance cycles from the literature and manufacturers' data, a sensitivity analysis is performed regarding the influence of scenarios for module B4, replacements. In the column named "low replacement", the minimum number of replacement and maintenance cycles over the studied 50-year period is shown and the most frequent replacement is shown in "high replacement". The highest scenario in this example resulted in a nearly a four-times increase in emissions, from 20 kg $CO_{2\text{-eq}}$/m^2 heated floor area to 79 kg $CO_{2\text{-eq}}$/ m^2 heated floor area. This implies nearly a 20% increase of the embodied GHG emissions if using the high scenario compared to the low one. Modules B2 and B4 in the figure represent both external replacement, maintenance of the building envelope and replacement of internal installations such as electrical, HVAC and elevator installations. The largest variation occurs in the expected lifetime of the windows, elevators, floor heating installations, electrical, ventilation and heating system.

Case study **DK3** is the only case study of a new building found to deal with a planned refurbishment scenario in the construction of a new building. From this study it becomes apparent that the life cycle refurbishment concept is difficult to deal with in cases of large scale interventions. In the comparative study of a regular single-family dwelling and a dwelling designed for adaptability, a rearrangement of inner walls and kitchen area is compared. Even though these rearrangements entail no further impacts for the adaptable house, the marginal impacts for the regular dwelling are still found to be insignificant, because by far most embodied impacts are associated with the building envelope. In the same case study, an extension of the building floor area of approximately 50% is also assessed as a refurbishment measure. This generates a significant increase of the embodied impacts, although some methodological issues apply, namely, how to properly assess a building life cycle where the functional service (the floor area) changes midway.

Case study **SE6** illustrates the EEG impact of a number of variations of fit-outs of office buildings to accommodate new business occupants. The study shows that payback-times for embodied carbon and embodied energy related to the installed materials are 5 years and 0.8 years respectively. Considering that office fit-outs may be undertaken several times during the life time of an office building, the results indicate that this frequent type of intervention could be significant in the building's life cycle EEG. Hence, scenarios for the B5 stage should preferably be included in the assessment of a new office building to provide a more comprehensive assessment.

2.9.4 *Energy supply scenarios (module B6)*

The B6 module may not in itself be relevant when analysing embodied impacts from the building life cycle. The module does become relevant however, when additional analyses of payback-time for embodied emissions are performed.

Example from the Annex 57 case studies

This can be seen in the **NO1** case where the environmental profiling of a residential net zero emission building (ZEB-OM, i.e. accounting for modules A1-A3 + B4 + B6) with PVs is carried out. Georges et al. (2014) conduct an evaluation of the payback-time of the embodied impacts from the **NO1** case where an analysis of different electricity grid scenarios is performed to test the robustness of the building concept. Figure 5 shows the conceptual details of embodied $CO_{2\text{-eq}}$ emissions pay-back when applying two different electricity grid mixes, one national and one synchronous grid of Continental Europe (UCTE).

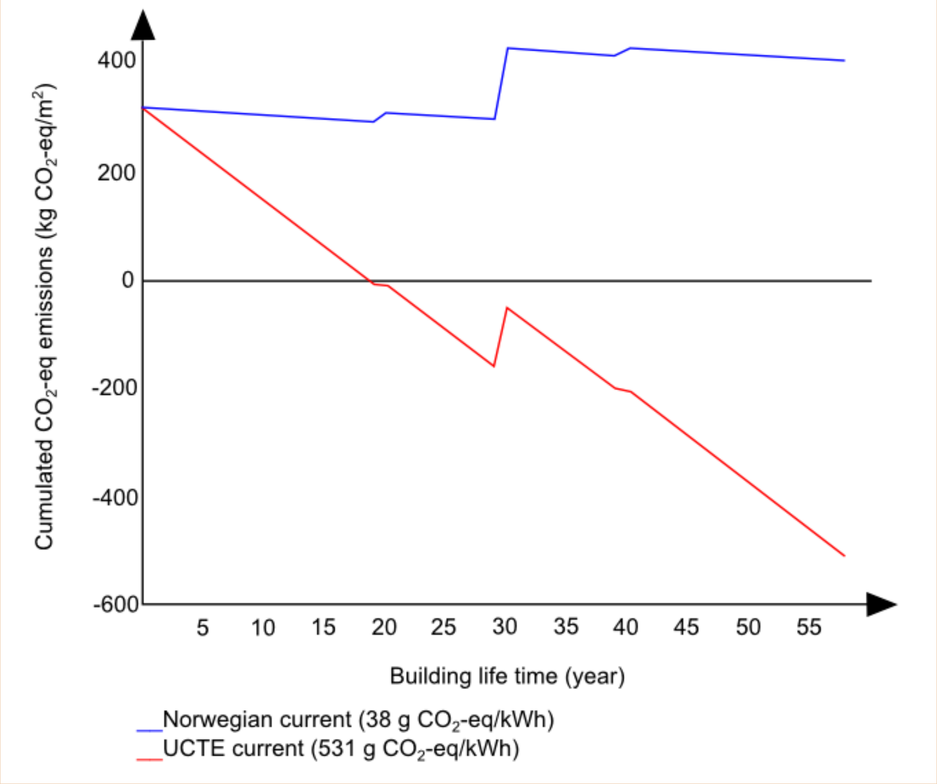


Figure5. CO_{2eq} emissions payback time of the embodied impacts via the electricity generated onsite during the building life time. Figure based on Georges et al. (2014)

As shown in the figure, the payback time when applying the UCTE scenario is less than 20 years although, when applying the national Norwegian scenario, the substitution of grid electricity by electricity generated onsite will not be able to offset the embodied impacts of the building itself. The full details of this work and of the electricity scenarios can be found in the paper by Georges et al. (2014).

The dependence between the building's PV electricity production and the payback of embodied impacts can be intuitively understood: the electricity produced by the on-site PV panels will be credited by the selected CO_{2eq} factor so that, using higher factors credits for the net PV export will counterbalance embodied impacts more quickly. Results from the study show that in the specific context of low CO_2-eq factors for electricity, the ZEB-OM balance becomes unattainable (Georges et al., 2014).

2.9.5 *Scenarios for the end-of-life stage (modules C1-C4)*

Scenario building for the end-of-life stage of the building is distanced in time by the length of the use stage. The actual processes used for end-of-life processes are thus difficult to foresee, primarily because of the lack of knowledge on the future value of waste as a resource. The value of the waste as a potential resource determines the technology used for the process and thus the embodied impacts, although the time perspective makes it additionally difficult to foresee the exact technology and associated impacts.

Example from the Annex 57 case studies

In all the analysed Annex 57 case studies, the approach taken is based on current practice for the waste handling of building materials. The exact processes for each material may thus vary from country to country or even on a regional level from municipality to municipality.

There is great variation in results between different waste treatment measures for the same material. An example of this is seen in the **UK9** case study about a multi-storey residential building built with wooden structure where different waste scenarios for the treatment of construction wood are investigated. Direct reuse is the most favourable options with savings of 959 tonnes of CO_2-equivalents, whereas incineration without energy recovery is the least favourable option with a load of 244 tonnes of CO_2-equivalents.

2.9.6 *Scenarios for benefits and load beyond the system boundary (module D)*

The life cycle stage of benefits and loads beyond the system boundary is likewise based on distant future scenarios. Because of the lengthy time perspective of assessing buildings, often 50-100 years, the results of these scenarios are subjects to some degree of uncertainty. Additionally, the inclusion of this life cycle stage may in some instances result in double counting of benefits and loads. Hence, European standards require that the results are reported separately from the results of the rest of the building's life cycle.

From the Annex 57 case studies, no examples are found on the significance of benefits and loads. However, in some cases found in existing literature, the potential impacts are investigated. An example of this is found in the study by Blengini (2009), where the reinforced concrete used in a multi-storey residential building complex was analysed. The demolition and subsequent waste processing and recycling as aggregate and steel scrap were documented and analysed in terms of impacts. The study concluded that compared to the environmental burdens associated with the production of concrete for the building shell, the recycling potential was 29% and 18% in terms of life cycle energy and greenhouse gas emissions respectively.

2.10 Building inventory

Apart from scenarios determining factors of use of materials, the results of a building LCA are also determined by the quantification of the building materials, namely the building inventory. From the Annex 57 case studies, two issues influencing the calculation set-up of the inventory can be identified: the level of detail and the source of data.

2.10.1 *Level of detail*

The building inventory's level of detail should preferably be aligned with the purpose of the study to ensure that all inventory contributions important to the impact results are included in the assessment. The level of detailed inventory information is naturally dependent on the design phase at which the assessment is carried out, such as early design, detailed design or as-built phase. Furthermore the access to detailed information can present a problem leading to a higher level of assumptions being made for the inventory at early design phase.

Example from the Annex 57 case studies

An example of early design versus as-built can be seen in the Annex 57 case studies **NO1** and **NO4** respectively. **NO1**, which is a concept model, is representative of early phase design and **NO4** represents as-built where a more detailed material inventory was available. The results show a more than doubling of emissions depending on the level of detail depending on the phase of design. The results show that **NO1** has 7.2 kg $CO_{2eq}/m^2/yr$ and **NO4** is responsible for 18 kg $CO_{2eq}/m^2/yr$. However, the case study author notes that there are a number of methodological reasons for the disparity in embodied emissions, such as the level of access to information and the classification of inventory data, in addition to differences in the material inventory between early phase and detailed design.

An additional point regarding the inventory level of detail can be seen in the **NO4** study where there is a variation in foundation design between the detailed design CAD/BIM drawings and the as-built phase. As further described in chapter 4.3, the concrete pier base has been omitted during construction, reducing the amount of concrete from 16m^3 to 9m^3. These modifications of design and material use in the actual construction process are to expect, and naturally the modifications affect the results of EEG when calculated for the same building but at different phases of the design process.

2.10.2 *Source of data*

The source of inventory data and the completeness of it can lead to different levels of quantitative assumptions used for the EEG calculations. In the Annex 57 case studies, the following sources have been identified and used separately or in a combination to base emissions calculations on:

- Bills of Quantities
- Architectural drawings
- Tender documents
- Product literature
- Building cost data (used for the input-output calculations in e.g. the **JP6**)
- REVIT/BIM (used e.g. in some of the Norwegian cases such as **NO1** and **NO2**).

Example from the Annex 57 case studies

Interpretation and manual cross-checking of material amounts and numbers is to be expected, regardless of the data source used. For instance, in case study **NO1** using BIM data, it was found through manual cross checking that the programme did not calculate the load bearing wood stud members in the outer and inner wall components. These quantities had to be estimated independently by the structural engineer. In this case the estimation is based on an estimate of 12% of the insulation volume. Another example found in case study **NO1** was that the BIM volume for the wood truss beam in the roof was 32.8 m³, whereas it was found that the actual volume of wood was 5.36 m³. In the example given, the BIM volume for the structural wood trusses in the structural decks and outer roof are based on a solid mass of wood, but in reality this mass comprises of a series of wooden beams. The quantity of wood has to be calculated by applying an estimated weight ratio of 2,3 to estimate the actual weight of wood in each wooden truss. Without these further steps and interpretation of the quantities, there would be a six fold over-estimation of emissions for the structural wood.

2.11 Background data

The type of background data used in a LCA study can have large influences on its results, which in turn affects the possibilities of comparing findings between different LCA studies. The challenge also applies to studies following the same standard, such as EN 15978, since the standard still allows different methodological choices. The reasons behind the variations in the background data used in different studies are many, e.g. inclusion of geographical characteristics, different methodological choices, data quality and availability etc. It is a complex subject which is difficult to cover completely. Therefore, this chapter includes only selected subjects identified in the Annex 57 case studies.

2.11.1 *Input-Output data vs Process-based data*

As explained in the **IEA EBC Annex 57, ST3 Report,** there are three widely used methods for data collection for LCA. These are:

1) Input-Output LCA
2) Process-based LCA
3) Hybrid method which combines the elements of Input-Output LCA and Process-based LCA.

The collection of the Annex 57 case studies consists of around 80 case studies from 11 countries. The 5 Japanese studies are Input-Output based and the rest are process based LCA. Generally, lower values can be expected from Process-based LCA compared to Input-Output due to the differences in method and the level of truncation within the two approaches (Crawford and Treloar, 2003, Nässén et al., 2007).

2.11.2 *Geographical variations*

According to EN 15978 chapter 10.3 on data quality, the geographical coverage shall be representative of the region where the production is located. This is partly due to the fact, that there are large variations in the composition of the energy mix and associated emissions for electricity production between countries due to their accessibility of different types of energy resources. The different approaches for the use of electricity data seen in building LCA studies (e.g. data for local or national electricity grid versus larger grids such as European electricity grid) can therefore have large influences on the results of studies. In the life cycle of a building, this subject is most important for LCA studies including the operational energy (module B6), which is out of the scope of Annex 57. However, the subject can also be important for embodied GHG emissions calculations for electricity intensive building materials. It is for example a question for several large building material manufacturers having production in different European countries if they should provide EPDs for their average European product based on European electricity grid or if they should provide several national EPDs for each country.

Example from the Annex 57 case studies

Comparison of the use of generic data vs. product specific national data was performed in the Norwegian case study **NO1**. Examples of the differences in the EG related with selected building materials are shown in figure 6. The total EG result of the case study resulted in 16% lower numbers by using Norwegian EPD data using the lower emission factor for the NORDEL electricity mix instead of using the Ecoinvent data.

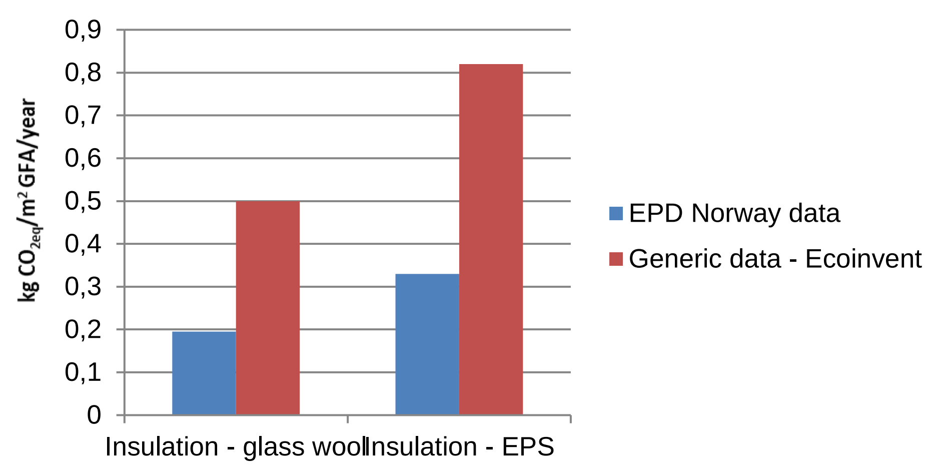


Figure 6. Excerpt of results from NO1 where generic data is compared with national EPD data. Two different types of materials are picked out from the NO1 case study template.

2.11.3 *Generic vs product specific data*

The level of the precision and detail provided in the data and information used in building LCA varies and often depends on the intended goal and scope of the study. Often data availability also plays an important role. The data can be generic data which means that the data is typical of the materials used, or data can be average data combined from different manufacturers of the same product. Lastly, data can be product specific, representing the actual material producer. Conventional LCA databases (such as Ecoinvent) and national building material databases (such as the German Ökobau) include considerable amount of generic or average data. EPDs can be and are created for associations of material producers, but most EPDs are product specific.

According to EN 15978 the choice of data depends on the scope and intended use of the assessment, the point of time in the decision-making process (e.g. sketch, final design, and construction), the availability of information and the importance of the data in relation to the overall importance of the study.

A study by Lasvaux et al (2015) compares generic environmental impact data from building materials EcoInvent with the corresponding values from the French construction EPD database INIES. For GWP and Primary energy demand the deviations are approximately 25 % although the deviations for other impact categories can be much higher (Lasvaux et al, 2015).

Example from the Annex 57 case studies

Comparisons of the use of generic data vs. product specific data were performed in two Norwegian case studies, **NO1** and **NO4**. Both case studies evaluate the influences of using Norwegian Environmental Product Declarations (EPDs) instead of EcoInvent data, making data more representatives for the Norwegian context. In figure 7 a comparison of generic and product specific data for the **NO1** study is shown.

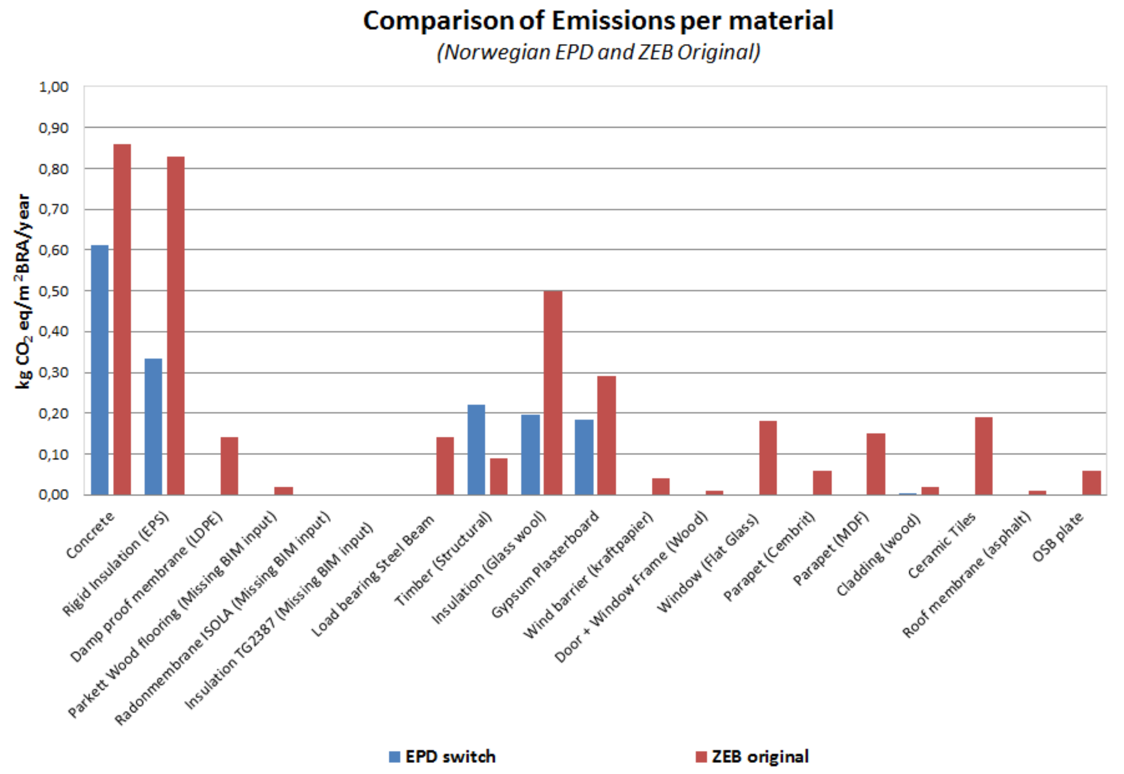


Figure7. Norwegian case study NO1. CO_2 emission comparison between ZEB original study and EPD switch for main materials inputs

Naturally, product specific EPDs do not per se present lower values of potential environmental impacts than generic data does. In the **NO1** and **NO4** cases however, the EG results of the buildings are lower when the product specific EPD data is used. This is mainly due to the geographical representativeness of data being changed at the same time, as mentioned in previous section and the difference in emissions of the electricity grid mix.

2.11.4 *Carbon sequestration and carbon storage*

Carbon sequestration and storage is relevant for the use of building materials of biological origin. Carbon sequestration is understood as the carbon that has previously been absorbed from the atmosphere and is now temporally stored in the material. As explained in (Brandao et al., 2012) and the **IEA EBC Annex 57, ST1 report**, there are different approaches for how to account for carbon storage in LCA, and the different approaches can lead to large differences in the results of embodied GHG emissions. In short, the differences relates to whether or not timing of emissions relative to removals is considered. As the storage of carbon is only temporary, the carbon sequestration principles should be balanced in the end-of-life stage where decomposition or incineration of the wood results in release of the same amount of greenhouse gas emissions as those initially stored[6]. However, systems boundaries often do not include the end-of-life processes, which leads to a distorted view of the actual impacts associated with the use of wood.

There is still no consensus on the most appropriate method of consideration and quantification of temporal storage of carbon, and the standards, such as EN15978 and EN15804, have no recommendations on the issue. Therefore, it is important that the decision to include or exclude carbon storage in data, such as EPD's and national databases, is considered in the Product Category rules (PCR).

Example from the Annex 57 case studies

The methodological differences are reflected in the Annex 57 case studies, where different approaches are seen. The cases studies from Austria, Denmark and Germany use similar approach that includes temporal storage of carbon. Figure 8 displays the CO_{2eq} details of Austrian case studies **AT1-AT3** and **AT5**, which account for carbon storage in the product stage, although there is no counterbalance from the end of life processes where the carbon is released again. The figure below illustrates how the storage of carbon in some cases, particularly the **AT5**, contributes significantly to the total EG as a result of the impacts from the product stage from other associated, GHG emitting processes.

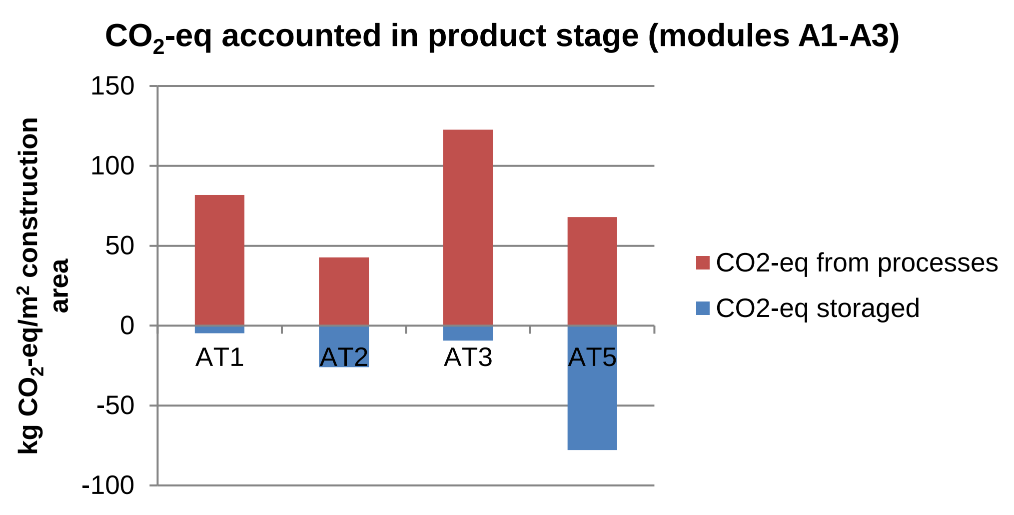


Figure8. Embodied GHG emissions from cradle to gate of Austrian Annex 57 case studies. Bar charts show contributions from processes as well as the temporarily stored CO_2 in wooden materials

2.12 Indicators and reference units

IEA EBC Annex 57 focuses on embodied energy (EE) and embodied GHG emissions (EG). EE and EG (or EEG as a common reference) are generally understood as the energy consumed and the CO_2-equivalents released in the life cycle stages of a building other than the operational (i.e. for space conditioning, water heating, lighting etc.) (Dixit et al., 2013). Further understanding of EEG is not unambiguous. The **IEA EBC Annex 57, ST1 report** identifies the following unclear definitions and/or differences between existing studies with regard to EE:

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[6] Note that emissions from decomposition of wood could lead to even more GWP than balanced by the sequestered and stored CO_2. This is due to the decomposition process potentially creating other and stronger greenhouse gasses e.g. methane.

- Limiting EE to ‘from cradle to end of construction’, or relating it to ‘from cradle to grave’ of buildings (i.e. including end of life)
- Accounting in EE for primary energy (e.g. natural fuels needed for producing electricity), or only for energy directly used in processes (final energy)
- Including or excluding feedstock energy, i.e. energy carriers used as a basic resource for and thereby stored in materials produced (e.g. oil in fossil plastics.
- The extent to which EE covers renewable energy or not.

These choices for EE are also relevant for EG originating from fuel combustion. Also, non-fuel related CO_2 emissions may occur, for example, from specific chemical reactions as occurs in cement manufacture, CO_2 emissions from incineration and landfill, sequestration and storage of atmospheric CO_2 during the growth of biomass. Unclear definitions and/or differences between existing studies with regard to EG include:

- The extent to which carbon sequestration and carbon storage in materials is included or not in EG
- Including or excluding other greenhouse gases, other than $CO_{2,}$ in EG

The position of Annex 57 is that these methodological choices with regard to EEG should be clearly stated and reported. This is explained in detail in the **IEA EBC Annex 57, ST1 report**. In practice however, it is difficult to interpret the extent to which the definitions are actually included in the Annex 57 case studies. For instance, it is often unclear whether results of cumulative energy demand (CED) actually accounts for both renewable and non-renewable demands or only for the non-renewable cumulative energy demand.

2.13 Performance indicator

There are a variety of ways to present the impact results from a building LCA and the choice of performance indicator largely depends on the purpose of the study. Possible performance indicators include results in total, per m^2, per m^3 or per occupant. A coupling with space and time related indicators are the preferred way of communicating results, most often as impacts per m^2 per year, e.g. kg $CO_{2\text{-eq}}/m^2$/year.

There is a risk that too narrow focus on this type of performance indicator may hide the absolute impact results of a building. A large building and a small building could show exact the same values of EE and EG when calculated per m^2/year. However, if the smaller building is able to provide the same functional services, the absolute EE and EG value of the smaller building are less than the larger building. This theoretical example serves to show that the design of the function of the building is a significant parameter in to the reduction of the embodied impacts.

2.13.1 *Definition of area*

There exists an ambiguity in the indicator used in the calculation of floor area used for the m^2. In some countries, such as Norway, the calculation of the heated floor area is measured to the inside of the wall, whereas in other countries such as in Japan and Denmark, this area is calculated to the outside of the wall. Furthermore, there are different definitions of gross, net or available areas, which further complicate the comparison of buildings even on the basis of only the area used in the performance indicator.

2.13.2 *Operative performance*

An alternative approach to presenting embodied emissions with an indicator linked to the building size (m^2) and the reference study period, RSP, can be to present the results in terms of occupancy or other term denoting the user potential of the building, thus highlighting the principle of optimising the efficient use of building space. In this regard, principles of adaptability can be a valuable aspect in assessing the individual buildings. This concept of adaptability is examined in the previous IEA EBC Annex 31 work .

2.14 Conclusion

This chapter summarises the extent to which the numerous methodological choices impact the final EEG results. It is important to understand the parameters that affect these methodological choices in order to identify the key EEG reduction strategies as presented in chapter 4, because what may present itself in a case study as a useful strategy to reduce EEG could also be affected by the calculation and system set-up used for generating the presented results.

The actual reported results of the IEA EBC Annex 57 case studies show a significant variation as a result of the different choices made in the types of system set-ups. These variations are caused by the following parameters:

- Purpose of study: Scene-setting for the sub-sequent choices of system set-up
- Reference study period for the building: E.g. whether the required service life or an arbitrary number used
- The system boundaries: E.g. whether the construction stage EEG are included in the calculations, and whether the transport of workers is included in the calculation of construction EEG
- Scenarios for the building: E.g. the scenarios made for the service life of materials or scenarios for the end-of-life of specific materials
- Inventory level of detail: E.g. whether the inventory is based on drawings, BIM, or as-build descriptions. Or the extent to which the material inventory includes all technical equipment and installations etc.
- Background data: E.g. whether the data process LCA based or IO-LCA based. Whether data is product specific or generic. The extent to which carbon storage is accounted for or not.
- Performance indicator: Definition of what is included in the area used in the results and whether these are reported per GFA or NFA.

The findings of the analyses in this chapter do not conclusively identify which of the parameters has the largest impact on EEG results. A main reason for this is that it is not possible to conclude to what extent do the methodological choices made in the calculations and the specific physical building characteristics influence each other, and which has the greatest influence on the resulting EEG. For this reason an important conclusion is that increased transparency regarding methodological choices in EEG building studies are necessary. Recommendations and templates to accomplish such transparency are presented in the **IEA EBC Annex 57, ST1 report** and illustrated in the case study templates of the **IEA EBC Annex 57, ST4 Case study collection report**. Also, standards still lack in certain aspects regarding methodological choices. For example there is still no consensus on the most appropriate method of consideration and quantification of temporal storage of carbon, and the standards, such as EN15978 and EN15804, have no recommendations on the issue.

3 A review of EEG results from the Annex 57 case studies

3.1 Introduction

This chapter analyses the IEA EBC Annex 57 case studies with the purpose of demonstrating the significance of different life cycle stages on the calculated embodied energy and greenhouse gas emissions of buildings. Furthermore, the significance of the building structure and design is investigated in terms of building elements and construction materials.

The case studies collected for the Annex 57 Subtask 4 work was the starting point for the analyses made in the report. The cases were supplemented with information from published literature where relevant and where specific information was lacking in the collected case studies. Note that only a limited number of the case studies are based on peer reviewed material and that references are indicated within each case study (see **EBC Annex 57, ST4 Case study collection report**).

In the analysis of the case studies, it is important to be aware of the background factors which distinguish the case studies. The case studies vary considerably, both in terms of methodology and system settings, as described in chapter 2 but they also vary in terms of actual building characteristics. In the **EBC Annex 57, ST1 report** a framework for structuring, evaluating and communicating building LCA results was proposed. However, as many of the Annex 57 case studies were carried out and completed before this comprehensive framework was developed, there was no consistency in neither the terms used, nor the methods followed and the background information documented in the case studies.

Appendix I shows a summary of the background set-up for the Annex 57 case studies. From this table, information about database, life cycle stages included, reference study period and building concept and type is apparent. The Austrian case studies (**AT1-AT3**, **AT5**), the Swiss case studies (**CH1-CH13**), the German case studies (**DE1-DE4**), as well as the Danish case study **DK4(a-g)** are comparable in terms of method used in each national group because the LCIA calculations are performed within a certification framework, thus ensuring a level of consistency. These types of national profiling calculations are in contrast to many of the other case studies, where different issues of methodological or design relevance has been tested as main goals of the studies.

Each varying parameter may not in itself be crucial to the direct comparison of the case studies; however, when added altogether in different combinations for different studies, a substantial disparity becomes obvious. It is however possible to extract patterns regarding the factors which influence the final results of the case studies which are presented in the following section.

3.2 Impact from different life cycle stages on EE and EG

The values describing the life cycle EG from the Annex 57 case studies vary between 0.3 and 20.3 kg $CO_{2\text{-eq}}/m^2$/year. The ranges for both EE and EG are wide, but as described in chapter 2, they reflect a large variation in specific building design and not least case study set-up, system boundaries and even reporting format. The difficulties in comparing results from building LCA studies are further discussed, for example in Optis and Wild (2010) or in the SuPer Building project about benchmark values for European buildings (Häkkinen et al, 2012).

In the following section, aggregated results of EE and EG from case studies are presented for:

- cradle-to-gate results (life cycle modules A1-A3 according to CEN TC 350, see Figure 1)
- cradle-to gate + replacement results (modules A1-A3 + B4)
- cradle-to-gate + replacements + EoL results (modules A1-A3 + B4 + C3-C4).

Note that there is a large disparity even within the case studies about the use of terms to describe the life cycle stages and the actual processes within these stages. The following analyses include the cases where results from the relevant life cycle stages are reported, either directly as numbers or indirectly through graphs. For the latter, the numbers behind the life cycle stages have been estimated. Thus, the exact numerical results are interpreted with some level of uncertainty which should be kept in mind when using conclusions based on the analyses.

Furthermore, numbers for EE are reported in many case studies without specifications on whether it is total, non-renewable or renewable. In the following analyses, results reported as non-renewable primary energy demand (PEnren) or non-renewable cumulative energy demand (CEDnr) are shown. Only for the analysis of the cradle-to-gate EE is the renewable primary energy demand included where such data is available.

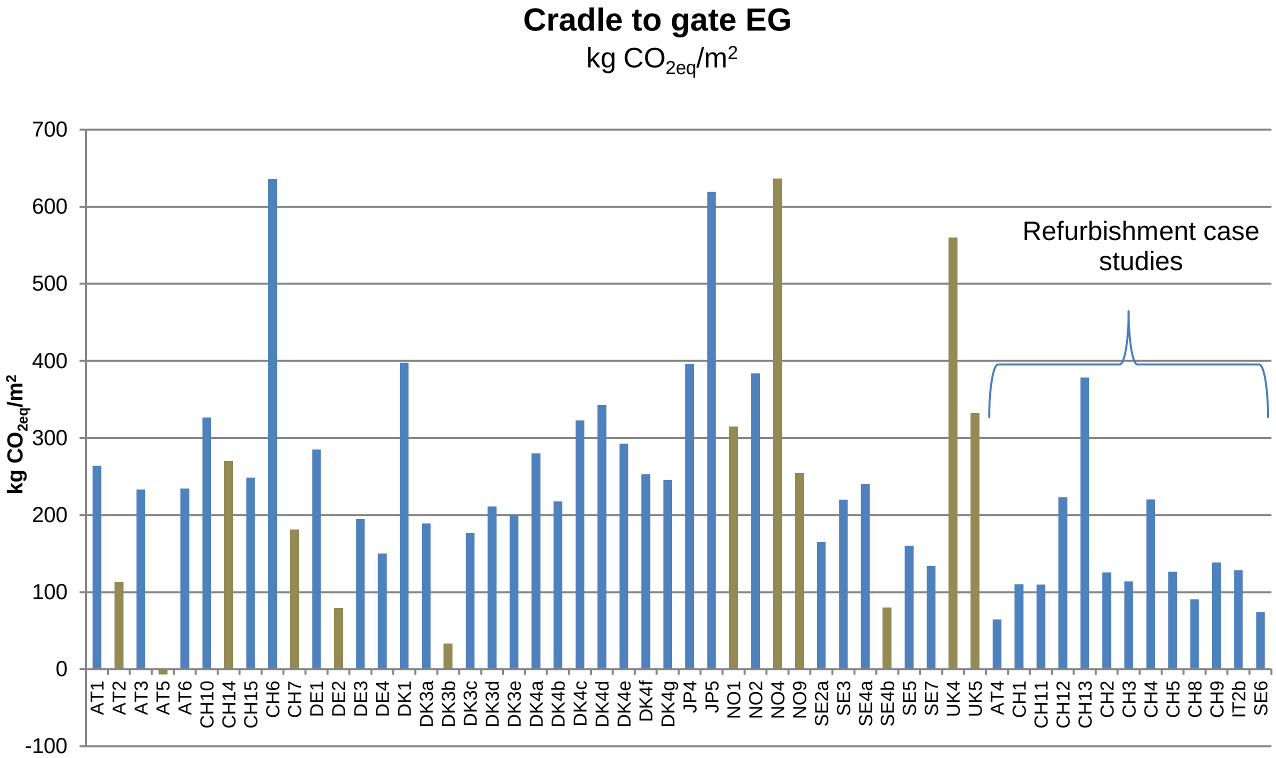

Figure 9. Cradle-to-gate EG from available Annex 57 case studies. Brown bars indicate constructions with wooden or hybrid wooden/concrete structures. Blue bars indicate constructions with concrete, steel or bricks as main materials for load bearing structures.

A negative number, as seen in the **AT5**, is achieved by a wooden building where carbon storage is accounted for in the calculations for the production stage. Other wooden structure cases like **DE2** (85 kg $CO_{2\text{-}eq}/m^2$) and **DK3b** (33 kg $CO_{2\text{-}eq}/m^2$) also produce low EG numbers. However, both DE and DK cases are built on the basis of the Ökobau database where carbon storage in wood is accounted for, and the results are thus very much dependent on the system of the background data used.

The structural use of wood does not automatically result in the absolute lowest EG. This is obvious from figure 9 where buildings with a hybrid or full scale wooden structure are marked in brown, as opposed to the cases marked by blue which represent structures of concrete, steel or bricks. The variations between the different cases which use hybrid or wooden structures are therefore made apparent. In relative numbers, case studies like **SE4**, **NO1** and **UK5** investigate the difference between concrete and wooden structures, each showing reduced EG from the wooden structure compared with the alternative concrete structure. However, the studies are early stage evaluations. Thus, the inventories may not include some of the additional coatings and fixings needed for the wooden alternatives.

Refurbishment cases of existing buildings seem to have less EG associated with the cradle to gate, at least when compared to studies using the same system set-up for calculations. However, within the refurbishment cases there are also large variations in results. Note that in the refurbishment of existing buildings, impacts from the production of materials used in the refurbishment actions is allocated to module A1-A3, i.e. the cradle to gate. For refurbishment scenarios applied to new buildings and new calculations, production of materials for the refurbishment actions is allocated to module B5 in the use stage of the existing building's life cycle.

Lower EG results are also associated with case studies, such as **SE2** with 165 kg $CO_{2\text{-eq}}/m^2$, where simplified calculations are performed, i.e. where only the main elements of the construction are included in the calculations.

Higher EG results are found in case studies such as **JP5** with 619 kg CO_{2eq}/m^2. In this study, both the design and calculation set-up influences results to a greater degree. For example, the building is designed to resist the effects of an earth quake which necessitated additional amounts of concrete and other materials for foundation stability to be included in the design. Furthermore, the study is calculated as an input-output LCA (see **IEA EBC Annex 57, ST3 report**) where all upstream processes are accounted for, thus generating higher end results than a similar process based building LCA probably would.

Another high EG result is seen in the **NO4** case, performed at as-built stage where detailed material inventory was available and which also included product specific EPD's. In this case study, the PVs and the aluminium mounting frames contributed with around 30% to the total EG and are thus considered a significant driver of emissions. In addition, this case study showcases the contribution to EG of including some technical equipment in the LCA calculations, an aspect further discussed in section 3.3.1.

EE of cradle-to-gate

Figure 10 shows the case study values of EE per m^2 building. Like the results for EG, results for EE for the cradle to gate stages varies considerably ranging from 943 MJ/m^2 to 13000 MJ/m^2. Note that the light blue bars indicate the additional amount of renewable primary energy for the buildings, however, it should be noted that this information is only available for the following case studies: **AT5-6**, **DE1-4**, **DK1**, **DK3-4** and **IT2a**. The grey bars indicate that no distinction about non-renewable and renewable shares of the EE has been made clear in the case study, thus the EE depicted includes the sum of non-renewable and renewable energy.

Buildings using significant amounts of wood in the construction, such as **AT2**, **AT5**, **DE2**, **DE4** and **DK3b**, present a larger share of renewable EE. The total of non-renewable and renewable energy used in these buildings was not found to be low. This is at least the situation for case study **DE4**.

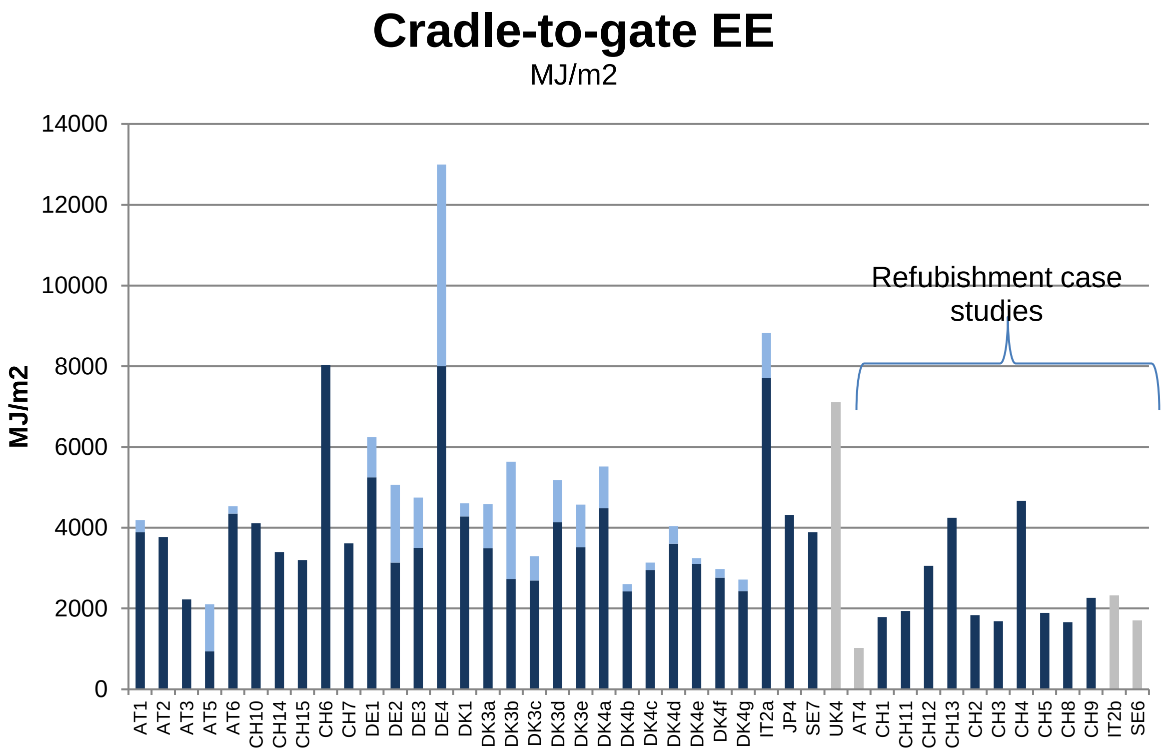

Figure 10. Cradle-to-gate EE from available Annex 57 case studies. Light blue bars indicate the additional amount of renewable primary energy for the buildings. Grey bars indicate case studies where the EE numbers are reported as a sum of renewable and non-renewable primary energy.

3.2.2 *Replacements (B4)*

EG of replacements

Figure 11 shows the contributions to EG from the production and the replacement life cycle stages of the relevant Annex 57 case studies. Naturally, the RSP of the individual studies will influence the contributions from the replacements, as longer RSPs will entail an increased amount of replacements to maintain the required building service. The Korean case studies **KR1-KR5** are marked in orange bars as the numbers reported in the case studies present the total EG of production as well as the replacement life cycle stages.

The **DK4a** and the **AT5** studies are unique in comparison to the rest of the studies. **AT5**, as mentioned in section 2.11.4, is a wooden structure building where carbon sequestration and storage is accounted for, thus leading to a negative number in the production stage EG. The replacements carried out for this building are responsible for a relatively large share of the total results. For the **DK4a** study, the negative numbers are caused by the replacement of wooden components. No other materials than those of wood are reported as part of the replacement scenarios. However, the design of the building does not suggest that wooden components would be the only replacements performed within the 50 years. Thus, the service life scenarios for replacement of, for instance, technical equipment and windows (> 50 years) are set at an optimistic scale.

Wooden constructions with low initial production EGs based on carbon storage accounting, such as **AT2**, **AT5**, **DE2** and **DE4** seem to present higher shares of EG from the replacement stage. This is not surprising, since the numbers from the initial production are that much lower than other buildings. The same relationship is seen with the refurbishment case studies where initial EG from the production stage are lower compared with regular new-build.

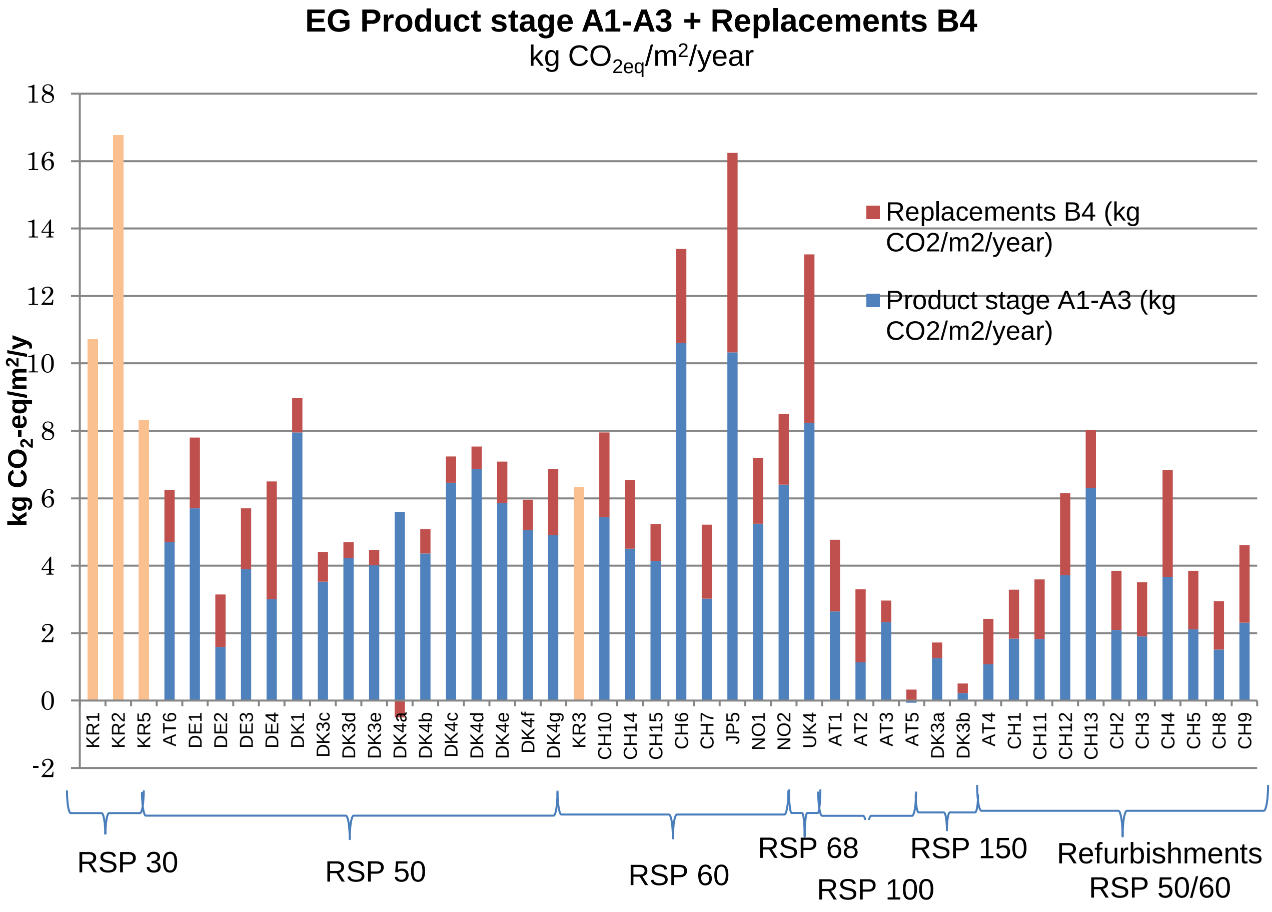

Figure11. Cradle-to-gate + replacement EG from available Annex 57 case studies. Orange bars indicate case studies where reported results is a sum of production and replacement impacts.

EE of replacements

Figure 12 shows the contributions to EE (only non-renewable) from the production and the replacement life cycle stages. The share of the building's EE from the production (A1-A3) and replacement (B4) stages varies between 12 and 52 %. This may be explained by some of the same drivers as identified with the EG regarding low initial production EE and correspondingly higher shares of replacement EE. However, additional drivers are not possible to detect based on the available information in the case studies.

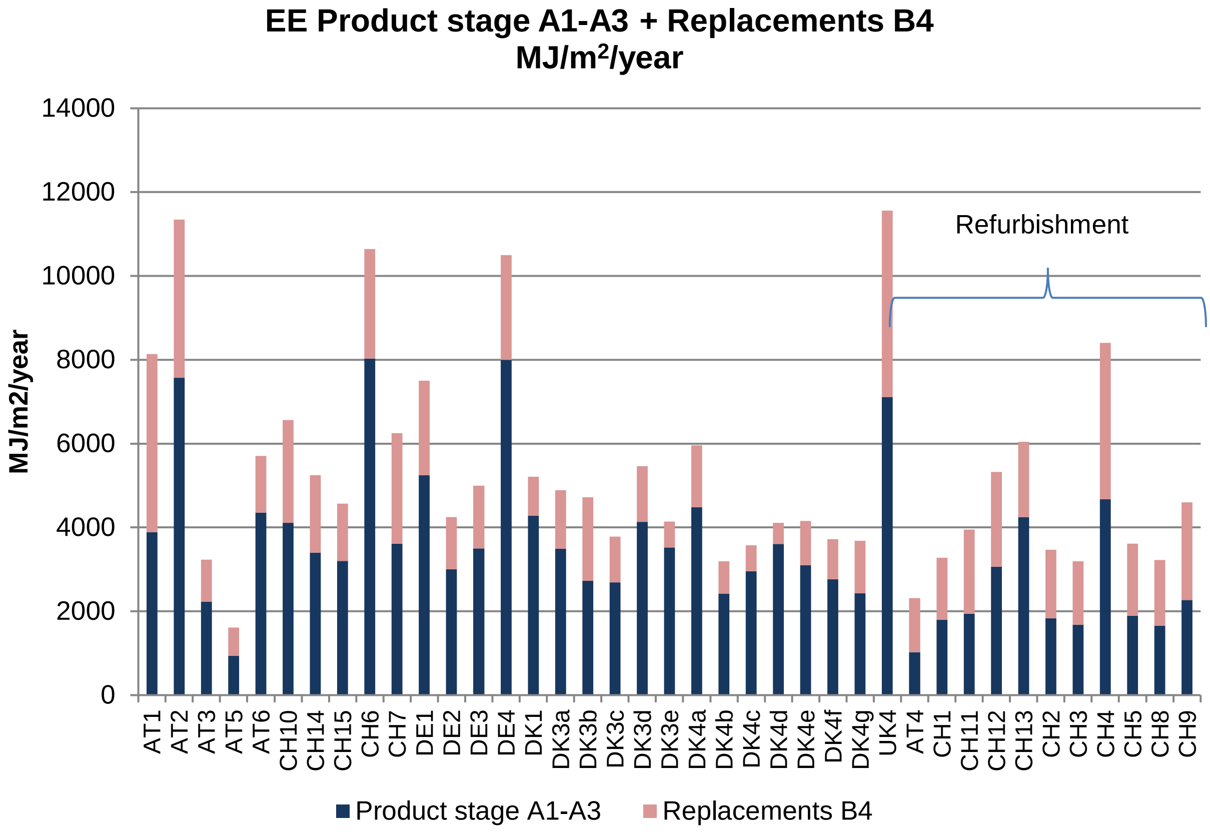

Figure12. Cradle to gate + replacement EE from available Annex 57 case studies

3.2.3 *End-of-Life*

Figure 13 shows the relative EG results of the three life cycle stages: production, replacements and end-of-life (EoL). The contribution from the EoL varies from 5-25 % in the included cases.

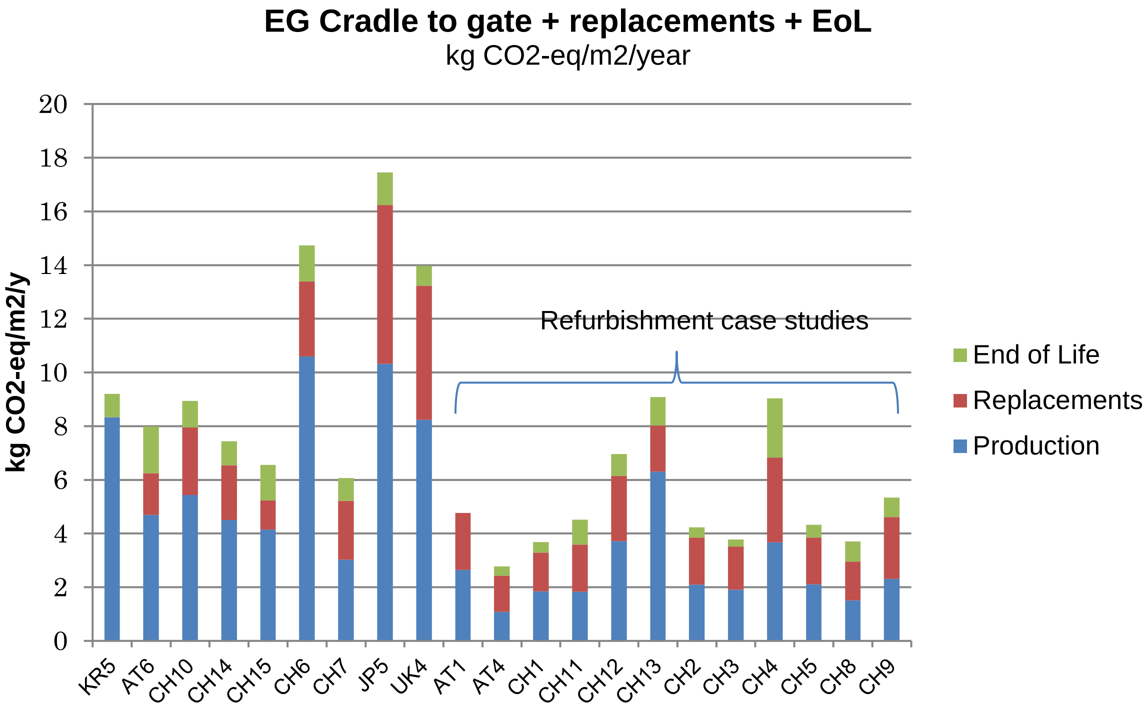

Figure 13. Cradle to gate + replacements + EoL EG from available Annex 57 case studies.

Mainly Swiss case studies report on the end-of-life contributions to EE as shown in figure 14. In all cases the contribution of end-of-life processes to EE is less than 10%, except for **AT4** where end-of-life processes amounts to 15 % of the total of cradle to gate, replacements and end-of-life stages.

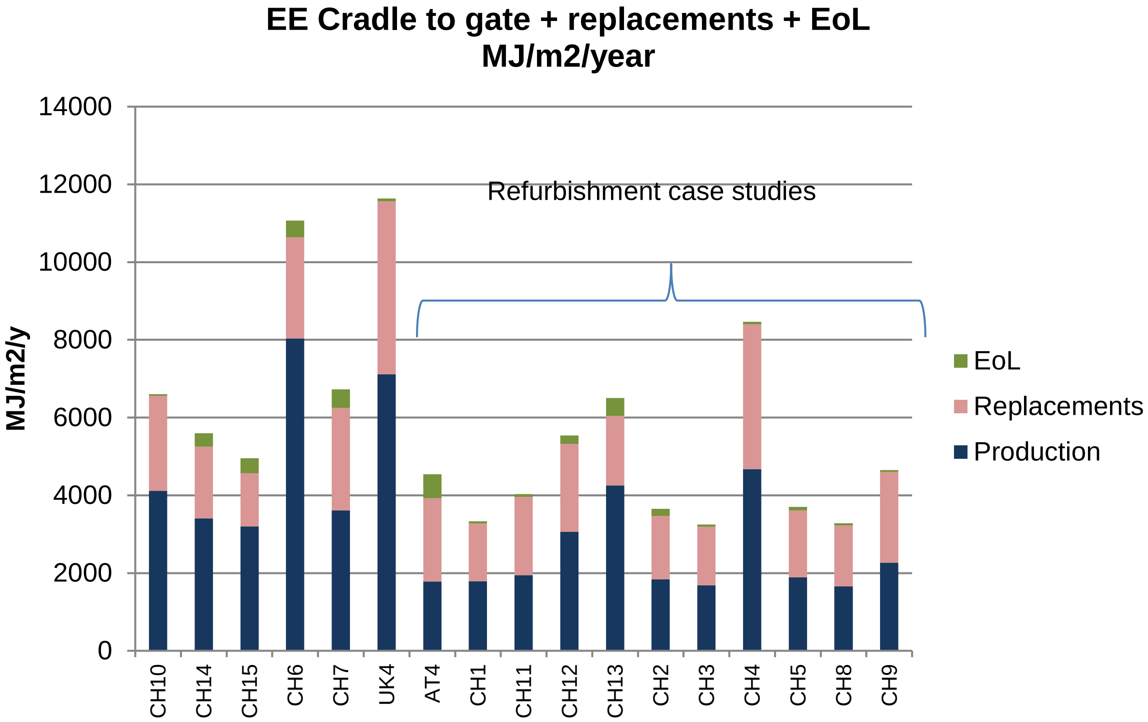

Figure 14. Cradle-to-gate + replacement + EoL EE from available Annex 57 case studies

3.3 Building design and structure

3.3.1 *Understanding importance of building elements*

The findings of the Annex 57 case studies show that the organisation of the building elements does not follow any harmonised approach. Thus, the case studies which report the significance of building elements do so in different manners and include varying elements. For instance, the **UK4** study of St Faith's School concludes that up to 30 % of the EE is related to the assembly category of "fittings, fixtures and furniture". This is the second highest contributing category to the study's EE, only surpassed by the category of "superstructure". In spite of this seemingly high contribution, the category of "fittings, fixtures and furniture" is not accounted for in any other of the Annex 57 studies. However, fittings may well be included in other studies but reported in the component where it is used, for example, in the wall or ceiling. A direct comparison between the case studies is therefore not possible in this respect.

The purpose of each building LCA study will to some extent decide the way elements are organised and at which level of detail the inventory is made, for example, the decision whether or not to include or exclude furniture or surface treatments. Thus, the categorisation and organisation of different elements is found in many different forms. In its most simplest form, categories of building elements are found to cover three different elements; floor&roofing, walls and foundations as is the case in a study by Haapio and Viitaniemi (2008). More elaborate categorisation is made in the case study by Thormark (2002) where contributions from 14 different categories are specified.

The Annex 57 case studies operate with variations from over categories of 5-10 building elements. The Swedish case studies **SE2-SE3** are among the studies with fewest element categories. These studies are based on simplified calculations for early design purposes, and the level of categorisation thus follows this simplified approach with only four categories consisting of:

- Internal walls
- Floor structure
- Basement
- Attic, including the roof
- External walls, including the windows and doors

Slabs generally contribute with large shares of the total EG of multi-storey buildings. This is for instance the situation in case studies **SE2a**, **SE2b**, **NO1**, **NO2** and **DK1**.

Technical equipment

Technical equipment is included in greater or lesser extent in several Annex 57 case studies (**DE1-DE4, JP1, JP5, JP6, JP7, NO1, NO2, NO4, NO9** and **SE2b**). It can be seen from the results that the technical equipment influences EEG considerably when this category is included. In the German studies **DE1-D4**, the technical installations account for 18-46% of the life cycle EG in a building and 12-30% of EE. In case study **DE4** (figure 15)**,** the results show the highest contribution of the technical systems seen in the German case studies (46% of the life cycle EG and 27% of the EE. This case study is for a new school building with structural parts composed of low-impact wood load bearing structure. The operational energy for the building is covered by electricity produced by PV (including electricity for heat pumps). The building does not include more technical systems compared to average buildings. However, it was found that the contribution to the embodied impacts due to the additional technical systems considerably lowers the impacts related to the operational energy of the building.

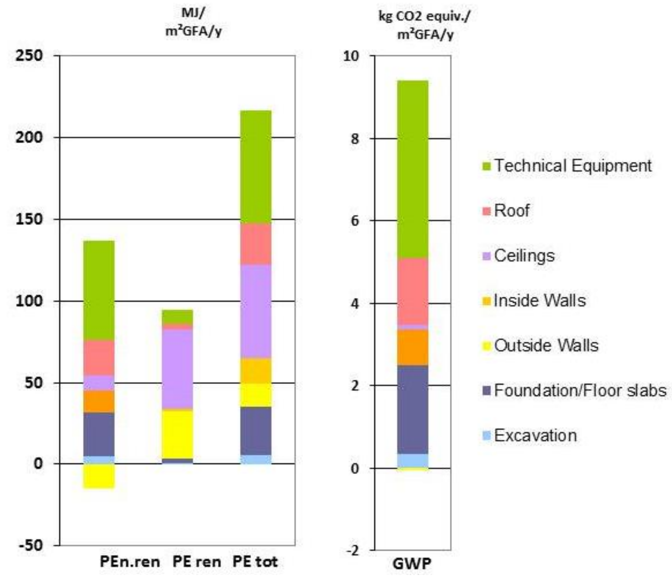

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Figure 15. Results of DE4 case study showing the contribution from the construction elements for the production stage, replacements and end-of life treatment of the materials divided into 7 different building elements.

The Japanese case studies also include embodied impacts for equipment, for example, **JP7** (figure 16) is a study of a renovated multi-storey office building where mechanical and technical equipment account for 33 % of the total reported EG from the renovation. For a newly constructed office building of the same standard, the **JP7** study reports that 19 % of the total reported EG can be ascribed to the mechanical and technical equipment.

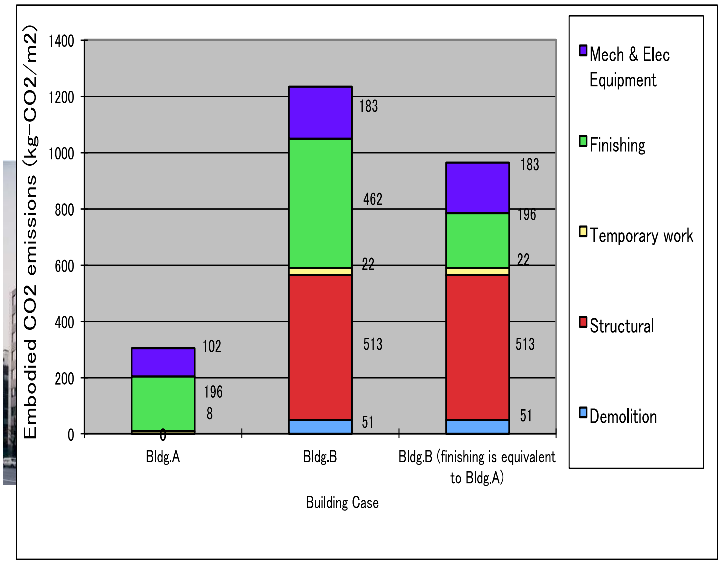

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Figure 16. Results of JP7 case study showing the contribution from building elements including mechanical and technical equipment.

The installation of PVs is common in many new buildings as a measure to obtain a low-energy profile. In the Norwegian case study **NO1** which is a low-energy ZEB-building built of conventional materials, the PVs are shown to contribute with as much 32 % of the total EG. The study is based on a single-family home in two storeys and the PV installation is sized to deliver 1130 kWh annually.

Refurbishment case studies

The Annex 57 case studies cover some building renovation examples where energy savings are achieved through a combination of optimised insulation performance and technical solutions. Where energy renovation processes do not entail renovation of structural elements, this otherwise significant building element, does not have a direct impact on the results of the embodied energy. Instead, the technical installations become significant contributors, as found in the case study **UK3**, where the boiler systems or solar water system alone contributes to 30-41 % of the total EG.

In a different renovation case, the Italian case study **IT2**, the energy renovation includes external insulation, as well as replacement and insulation of the ground floor concrete slab. As a result of this substantial replacement of concrete mass, the technical installations of boiler and PV system accounts for just 20 % of EG compared to the 80 % EG from materials.

3.3.2 *Materials*

Like the case of building elements, the building materials and their contribution to the embodied impacts is reported at many different levels of detail depending on the material inventory. For instance, the Japanese case study **JP1** includes a very high detail level of more than 70 categories of building materials used.

Concrete and metal as significant contributors

In most reported Annex 57 case studies, concrete and other cement based products seem to be the larger contributors to EG. In studies for traditional concrete/steel structure buildings, like case study **DK1**, **SE2a**, **SE2b** and **KR2**, contributions from concrete vary between 40-80 % of the total impacts from materials.

Other significant contributors include insulation materials as shown in some case studies for low-energy housing, such as **SE2** and **NO1** where they account for up to 40 % of the material related impacts.

Alternate building design strategies can lead to other materials gaining importance. For example, it can be seen even in alternate designs, such as the **UK9** case study which uses a wooden superstructure for a multi-storey residential building, concrete is still a significant driver for emissions due to the sheer amounts used in the foundations and slabs. The same is found in the case for the **KR5** case study of a single-storey residential building and **NO2**, a multi-story office building.

The results also show that metals used in building construction, such as steel for structural purposes and aluminium for profiling, also make significant contributions to EG as seen in the office building case study **KR3,** where the steel construction accounts for 65 % of the production impacts.

As for the few case studies reporting materials' contribution on EE, metals was also found to make dominant contributions, as seen in **DK1** where concrete accounts for 20 % compared to metals which account for 40 % of the material related impacts. In the **CZ1** case study, metals contribute with around 30 % of the material related EE in the reference building and insulation materials contribute with slightly more than 30 % EE.

However, it should be noted that the modelling of open-loop recyclable metals such as steel can follow different approaches, which affects the EG and EE results from the metal's life cycle significantly (see **IEA EBC Annex 57, ST1 report**)

The direct reuse of building materials, i.e. bricks, steel or concrete elements can in some cases lower the contributions from the materials used in the building. This is further described in chapter 4 of this report.

Wood and timber products

Wood products can be complicated to manage in international comparisons of building LCAs. This is due to the fact that different approaches exist concerning the inclusion/exclusion of carbon storage in the biomass (confer section 2.11.4). Thus, the actual EG figures for wood differ significantly between the relevant case studies. However, whether carbon storage is included or not, the use of wooden products for the load bearing structure and/or and finishing in several studies has been proven to be a favourable alternative to heavy materials such as concrete in terms of EG. This can be seen in the following case studies, **DE1**, **KR1**, **SE2b**, **NO2** and **UK5**.

In case study **UK9**, a multi-storey residential building is constructed using CLT-frames. In this study, different approaches to carbon storage are investigated and it is concluded that the use of sustainably managed wood justifies a 100 % carbon storage approach in this study. Results of the CLT structure option are thus, regardless of the end-of-life option for the wood, better than an alternative traditional construction using concrete and steel.

3.4 Conclusion

This chapter shows the reported results from the Annex 57 case studies and analyses the relative contributions to EEG from the different life cycle stages, building elements and different materials. In spite of the Annex 57 framework for structuring and reporting LCA calculations for EEG, the case studies are seen to present cases and numbers in various formats, reflecting the effect of the numerous methodological background parameters which affect the results, as presented in chapter 2.

The EEG results presented here illustrate the uniqueness of not just each building, but also of the set-up for each study and how these impact the results. However, despite these differences there are still some general trends which seem to be prevalent:

- The product stage (A1-A3) is the life cycle stage which contributes the most to the EG and EE for new buildings.
- For the refurbishment cases, the replacement stage (B4) contributes almost equally to the results as the product stage, although this is largely dependent on the product service life.
- The technical equipment installed in the buildings is responsible for significant contribution to the EEG, in some cases up to 46 %. However, it should be noted that the technical equipment is not always included in the assessments.
- Concrete and metals are the material types which contribute the most to the EEG of the case studies. In this regard, it should be noted that concrete is often used in large amounts, and that the profiling of metal can be vastly influenced by including or excluding the recycling benefits from the next product stage (module D).
- EG numbers and profiles related to wooden constructions are affected to a large degree by whether or not carbon storage is included. However, regardless of the approach, it can be seen that case studies investigating wood design alternatives for specific buildings present lower EEG results compared to the heavier solutions from concrete or steel. However, most of these studies are assessed at an early design stage. Thus, the extra fixtures and fittings needed for wood construction may not be included in the assessment, which would lead to an increase in the total EEG. Furthermore, the switch between these materials has not been evaluated with a consequential approach. Therefore it is not possible to conclude on a larger scale that wood is preferable to other materials.

The findings presented in this chapter thus highlight the parts of the building life cycle where changes in design or construction practice could help reducing EEG from buildings. The actual design measures which would potentially provide these emissions reductions are presented in the following chapter which focuses on design strategies for reducing EEG.

4 Design and construction strategies for reducing EEG

4.1 Introduction

This chapter discusses the potential of different design and construction strategies for reducing embodied energy (EE) and embodied greenhouse gas emissions (EG) (see Table 2). In order to do so, it primarily reviews the Annex 57 case studies. However, it should be noted that most of these case studies do not cover EE and only include EG. Therefore, only a few case studies provide a comparison of alternative solutions for reducing emissions, and several of the design and construction strategies identified in this chapter were found not to be specifically addressed in the case studies. As a result, additional, relevant case studies had to be sought in published scientific literature and these were then used to develop and illustrate these strategies.

Table 2: Design and construction strategies to reduce EEG, and relevant case studies collected as part of Annex 57

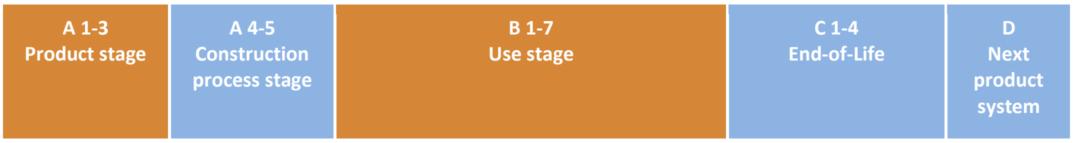
Strategies / measures	Building type				
	Residential (multi-family)	**Residential (single family)**	**Office**	**School**	**Stadium**
SUBSTITUTION OF MATERIALS					
Natural materials	SE2b UK9	KR5 UK5	SE5	UK7 UK4	
Recycled and reused materials and components		DK2, CZ1	KR3		UK11
Innovative materials	CZ2				
REDUCTION OF RESOURCE USE					
Light weight constructions	CZ2	NO1 NO4	NO2		
Building form and design of lay-out plan	SE4	SE3	NO1		
Design for low maintenance need					
Flexibility and adaptability		DK3a,b	SE6		UK8, UK11
Reuse of building structures	SE7		DK1		
Service life extension	SE7	DK3a	JP5 DK1		
REDUCTION OF CONSTRUCTION STAGE IMPACTS	UK3 SE7	UK5 NO4			
DESIGN FOR LOW END OF LIFE IMPACTS				UK7	

The relationship between operational and embodied energy (OE and EE) of buildings should also be noted. For example, a material with low EE may have a low insulating value and thus potentially increase the OE. These relationships need to be taken into account at an early stage when designing and constructing new buildings, because decisions during the early design phase have the greatest potential for minimising the whole life cycle energy.

In the following sections, design and construction strategies focusing on reducing EEG will be discussed and illustrated with the help of the selected case studies. The strong influence of calculation methodology and choice of system boundaries is not addressed here, since these topics have been discussed in chapters 2 and 3. However, it should be noted that as a result of the diversity of methodologies used in the case studies, the individual cases cannot be used to quantify reductions in general, but rather should be viewed as a means to illustrate the potential of different reduction strategies in various contexts.

For each strategy below, the underlying logic of the strategy is explained first, and then illustrated using the available case studies to demonstrate the reduction potential of each strategy. In the beginning of each section, the main calculation modules of EN 15978 are presented to highlight **(in orange)** in which modules the particular strategy mainly realises its reduction potentials (blue colour means that the modules have less or no importance). The key strategies presented in this chapter focus on design or construction changes of the building itself, and thus do not include emission reducing strategies and decisions such as importing materials produced in countries with a low-carbon electricity grid.

4.2 Substitution of materials



Material substitution is an important strategy since a large part of the EEG relates to material production (see chapter 3). In the following section, three strategies are investigated in the following order: the use of “natural” materials, the use of recycled materials and finally innovative materials. The rationale for using natural materials as a reduction strategy is particularly relevant if it is bio-based (which may constitute a carbon-sink until end-of-life), if the material needs less processing energy in the production or is used as “original” i.e.as found in nature. For recycled materials, the rationale for the strategy also includes less need for processing energy, as well as, for raw-material acquisition and avoiding of end-of-life emissions. Finally, the section on innovative materials covers case studies on materials specifically developed to substitute materials with high EEG.

4.2.1 *Natural materials*

The use of natural materials in construction has a long history, since non-natural materials practically did not exist or were very expensive to produce until the industrial revolution in the 19th century. In this report the definition of natural materials proposed by Pete Walker (2009) is used:

- Inorganic materials
    - Earth construction
    - Lime based materials

- Renewable plant based materials
    - Timber and wood based products
    - Crop by-products: straw; hemp shiv
    - Fibres: hemp; flax, sisal, kenaf
    - Bamboo; reeds

- Animal based products
    - Sheep’s wool
    - Additives (horse hair fibres; blood; casein; urine; excrement).

This section analyses the possibility of reducing EEG by replacing artificially-made materials with natural materials. Building structures can be sorted into three groups: load bearing structures, both vertical and horizontal; foundations; and non-load bearing structures. For non-load bearing structures, the focus is mostly on the thermal envelope and façade of the building since these structures have a large potential to reduce both operational and embodied energy and greenhouse gas emissions.

Main load bearing structures

Table 3 on the following page provides a list of case studies which illustrate the influence of natural materials in load bearing structure on EE and EG.

The main load bearing structure has to meet many requirements, such as bearing capacity, durability, service life, and fire resistance. Structures based on masonry, concrete or steel can easily fulfil these criteria and thus are very frequently used. A number of case studies performed in early design stage compare wooden and concrete load bearing structures. In the **UK5** case study (modules A1-A5, B6) comparing three scenarios, EEG is found to be lowest for the precast timber frame with factory-installed phenolic foam insulation. In the case study **SE5** (modules A1-A3, B6) a considerable reduction of building EG is achieved by replacing concrete slab within a wooden solid laminated slab.

Another alternative for load bearing building structures were found to be unfired clay products. The case study of Růžicka et al (2013) analyses the possibility of application of prefabricated rammed earth panels for both load bearing and non-load bearing interior walls in family houses. The results show a small reduction of EE and no reduction of EG for the rammed earth panels compared to the burnt clay bricks. In this study, the rammed earth panels were penalised by long transportation distances (350 km) and associated transport emissions. This is as result of the fact that in Europe earth is not commonly used as a construction material and even though earth as a raw material is usually locally available, only a few mining companies provide it. Thus, in the next study (Havlik, 2015, n.d.) the transportation distance of raw material was considered 30km, which would be realistic, if the rammed earth was commonly used in construction sector. In this case, rammed earth panels reduce EG by 80% and EE by 50% compared to burnt clay bricks (per m^2 of inner wall) and even more when compared to aerated concrete. The important advantage of rammed earth is its high mass, which is often necessary for inner walls to achieve sufficient acoustic and heat accumulation requirements, which are often found to have poor performance when using commonly used materials. Locally sourced rammed earth can therefore provide a good functional solution while also reducing EEG of internal walls.

A case study of Sodagar (2011) analyses the EG benefits of straw bales used as a material for load bearing walls. Five scenarios were proposed which use different material in the walls for a pair of semi-detached houses in the UK. Besides the straw bales variant, two variants of timber frame walls and two variants of masonry walls were studied, with an external surface of lime rendering and brickwork respectively. The EG was calculated including the production of materials, transport, construction process, and the end-of-life stage. The straw variant had the lowest EG even if carbon storage was not taken into account. This variant is also the cheapest of all variants proposed. On the other hand, the use of straw requires special design and construction details, since the straw bales need to be properly protected from moisture and pests.

Table 3: Case studies comparing man-made materials with natural materials used for load bearing structure.

Case study	Building type	Main materials (load bearing structure)	Reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
UK5	Residential	Panellised timber frame (MMC - Modern Method of Construction Larch facade replaced by bricks Masonry cavity construction Wooden construction	20 years	A1 - A5 B6	26 % lower EE for timber frame than the traditional masonry house. Even for scenario with timber frame half of impact belongs to the foundation, floor ground and substructure	35 % lower EG for timber frame than the traditional masonry house. Even for scenario with timber frame half of impact belongs to the foundation, floor ground and substructure.	
SE5	Office	Concrete construction Wooden construction	50 years	A1 - A3, B6		Different measures taken for to reduce total EG of house. Replacement of concrete slab by wooden solid laminated slab reduce EG from 4,1 to 3,1 kg CO_{2eq}/m^2, yr.	
UK7	School	Scenario 1: steel frame, concrete blockwork infill. Scenario 2: Cross-laminated timber.	60 years	A1 - A5, B1 - B3, C1 - C5, D	Materials EE is app. equal for steel and for timber scenario.	Materials' EG is about 30 % lower for timber than for steel scenario. (carbon storage is not included)	Recovery potential of timber (combustion) is higher than for steel (recycling).
UK9	Residential multifamily house	Scenario 1: Cross laminated timber superstructure, concrete foundations Scenario 2: reinforced concrete frame, steel facade		A1 - A5, C1 - D		Cross laminated timber frame option saves almost 62% of EG. The main difference between two variations is in EG of superstructure. Consideration of carbon storage plays an important role for the result.	
Růžička et al. (2013)	Residential family house	Scenario 1: internal walls consists of rammed earth wall panels Scenario 2: Internal walls consist of burnt clay lightweight bricks Scenario 3: Internal walls consist autoclaved aerated concrete	60 years	A1-A3	Rammed earth panels reduce EE by 50 % compared to burnt clay bricks and by 80% compared to aerated concrete blocks.	Rammed earth panels reduce EG by 80 % compared to burnt clay bricks and by 90% compared to aerated concrete blocks.	Density of rammed earth panels is three times higher than density. of ceramic lightened bricks and six times higher than density of aerated concrete.
Sodagar et al. (2011)	Semi-detached family house	Scenario 1: Straw bale external and party walls	60 years	A1-A5, B6, C1-C4		Scenario with straw bale walls reduce EG by 2-11% compared to other scenarios without carbon storage taken into account. The highest EG is in case of scenario 5 – brick-faced masonry.	

Foundations

Table 4 lists the selected case studies which show the high EE and EG contribution of foundations compared to the rest of the building.

Table 4: Case studies illustrating high contribution of foundation to the total building EE and EG.

Case study	Building/component type	Main materials (load bearing structure)	Reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
UK4	School	Timber I beams, plasterboard system	68 years	A1 - A5, B3 - B7, C1 - C2			
UK5	Residential	Panellised timber frame (MMC - Modern Method of Construction Larch facade replaced by bricks Masonry cavity construction	20 years	A1 - A5 B6	Even for scenario with timber frame half of impact belongs to the foundation, floor ground and substructure	Even for scenario with timber frame half of impact belongs to the foundation, floor ground and substructure.	
KR5	Residential	Timber frame	30 years	A1 - A3, B1, B4, B6, C3, C4		67 % of material related EG belongs to the concrete used because of floor heating system.	

As already discussed in chapter 3, the EEG of a number of case buildings (namely **UK4**, **UK5**, **and KO5**) using a timber superstructure is still considerable due to the use of mineral materials (concrete, masonry, plaster) in foundations and ground floor slabs. For example, in the **UK5** case study, in the scenario with a wooden load bearing structure, the concrete foundations, substructure and ground-bearing slab contributes to half of the total EG related to the material production (modules A1-3). For the **KR5** case study, the quantity of concrete used due to the floor heating system accounts for 67 % of the EG related to the material production.

Thus, it was found that reducing the EG of timber-structure buildings calls for research into alternative solutions for the foundation structure and substructure. Besides the use of low EG concrete, touched upon in section 4.2.3, concrete foundations can also be replaced by natural alternatives. A new system, based on clay and layers of geotextile ("Lasagna foundation") was developed in the Netherlands and is used in the ‘District of tomorrow’ near Heerlen (RiBuilT, 2013). Another alternative, emerging from traditional construction methods, are wooden foundations. This system is used in the United States and consists of lumber-framed foundation walls which are pressure-treated to withstand decay from moisture and damage by termites (Labs HI research, 2004). Other types of foundations may be steel ground screws, which is sometimes used for wooden houses. Nevertheless, so far, there are no LCA results which document the potential environmental benefits of these alternative solutions.

Non-load bearing structures

Table 5 lists case studies which show the use of natural materials to decrease the embodied impact of non-load-bearing structures.

Table 5: Case studies illustrating the reduction of EG and EE of buildings through the use of natural materials for non-load-bearing structures.

Case study	Building/component type	Main materials (load bearing structure)	Reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
CZ3	Accommodation facilities – refurbishment	Scenario 1: Combination of wooden frame and aerated concrete blocks, mineral wool Scenario 2: Combination of wooden frame and aerated concrete blocks, wood wool insulation Scenario 3: Combination of wooden frame and aerated concrete blocks, cellulose fibre insulation	60 years	A1-A3	9 % lower EE by using wood wool insulation instead of mineral wool.	13 % lower EG by using wood wool insulation instead of mineral wool.	
Wright (2012)	Insulation of solid walled house	Scenario 1: Inner insulation by dry-lining (mineral wool and vapour barrier) Scenario 2: Inner insulation by hemp-lime render		A1-A5		Significant saving of EG in case of hemp-lime variant due to the CO_2 sequestrated in hemp.	Lower thermal performance of hemp-lime variant.
Melià et al. (2014)	Research focused on plaster.	Scenario 1: Cement plaster Scenario 2: Hydraulic lime plaster Scenario 3: Clay plaster	30 years	A1-A3	About 60 % lower EE for clay plaster compared to cement or lime plaster.	About 75 % lower EE for clay plaster compared to cement or lime plaster.	
Tywoniak et al.	Bio-based curtain walls elements	Scenario 1: Wooden based curtain wall Scenario 2: Traditional metal based curtain wall	30 years	A1-A3	42 % lower EE for wooden variant	97 % lower EG for wooden variant (with carbon storage taken into account)	

The following section describes the findings of three case studies focused on thermal insulation, facades and plasters.

The thermal envelope of buildings often consists of large amounts of thermal insulation which increases with increasing requirements for operational energy efficiency. However, the most widely used insulation materials (mineral wool or polystyrene) have relatively high EEG and thus their contribution to the overall EEG of material production (modules A1-3) can become significant (see section 4.3).

The use of natural insulation materials could therefore potentially reduce environmental impacts. Case study **CZ3** compares three scenarios for the refurbishment of a mountain chalet. The refurbishment strategy is designed according to the Passive House standard and consists of the insulation of walls, roof and floor, replacement of windows and renovation of finishes. The three scenarios differ only by the type of material used for the insulation of the walls and roof. The ground floor insulation is the same in all three scenarios. The results show that the use of wood fibre instead of mineral wool in the wall and roof insulation can reduce the material EE of the whole refurbishment by 9% and EG by 13%. It should, however, be mentioned that most EEG is caused by the insulation used in the ground floor, which in this case consists of

800 mm of crushed foam glass. Thus, there is still high potential to reduce the embodied impact by finding other solutions for the ground floor insulation.

The study of Wright (2012) compares two systems for internal insulation of solid walled slate cottage in mid-Wales in the UK. Solid walled dwellings make up a big part of European housing stock and in many cases it is not possible to apply external insulation. Therefore, internal insulation is often the only possible way to insulate these dwellings but it is problematic, because it can lead to condensation in walls. This study investigates EEG in the module A1-5 phase, in-situ hydrothermal performance and interstitial moisture regulation of two insulating systems: conventional method which is dry-lining using mineral wool and vapour barrier and an innovative method which uses hemp-lime insulating render. Hemp and binder (in this case lime) is an insulating middleweight matrix which is applied wet into the form work to create wall or an insulating render. Results show, that hemp renders have a negative value of EG because it stores more carbon dioxide than is emitted during the production, transport and installation of hemp-lime insulation. There, the resulting emissions EG for 1 m^2 of wall with hemp-lime insulation is -4 $kgCO_{2eq}/m^2$ and with dry-lining is 903 $kgCO_{2eq}/m^2$. The disadvantage of the hemp-lime render is its weak thermal performance compared to mineral wool (used for dry-lining) which means, that the high EG associated with dry-lining insulation will probably be paid back by saving in EG from heating with steady state values of thermal performance, when compared to hemp. Thus, for achieving real EG savings by using hemp-lime render, its thermal performance needs to be improved.

Another example of non-load bearing structures with high EEG are metal based curtain walls, which are common in central and eastern Europe, where they are used for refurbishment of houses from the 1960's but they are also used in new buildings. The environmental impact of metal based curtain walls is high due to the metal content and the service life of these components is only around 30 years. A case study by Tywoniak et al. (2014) proposes a wood-based alternative for curtain walls called *'Envilop'*, figure 17. In this system, 93% of the weight consists of wood-based materials in its opaque section and 65 % in its transparent section. The EG and EE of the wooden and the traditional metal-based alternatives were compared. With the wooden alternative, the EE is reduced by 42% and EG by 97% compared to the traditional metal-based alternative. It should be mentioned, however, that carbon storage in wood was included in the calculation and this has a large influence on the results.

Figure 4. Scheme and photo of wood-based curtain wall (source: Tywoniak et al. (2014))

The external rendering system is also a large group which belongs to the non-load bearing structures group. Melia et al. (2014) made a comparative LCA of the production stage (A1-A3) of clay plasters compared with cement and lime plasters. Clay plasters are composed of sand, clay, vegetal fibres and possibly natural or synthetic additives if needed by improving physical or mechanical properties and change of colour. The study showed, that the clay plaster has EE and EG by 60-70% lower compared to the lime plaster, depending on the typo of clay plaster. The EE and EG of the cement plaster is about 8 % lower compared to the lime plaster. Clay plasters have other important advantages, for instance, with respect to hydrothermal comfort, since they can absorb and release water vapour from air and, hence, help to keep a balanced indoor hydrothermal microclimate. Furthermore, the preparation of clay plasters is simple and it can be often done using local resources (Melia et al, 2014). Nevertheless, this case study only considers the production stage of compared plasters and does not include maintenance scenarios. Further research is therefore needed to examine the durability and service life span of the clay plaster.

The application of natural materials in the construction sector has historically been widely applied in vernacular architecture when local, unprocessed materials were the raw materials used to build with. With the onset of industrialised age and construction, new materials were developed and promoted. Nowadays, most natural materials used in construction include timber, wood wool, unburnt clay and straw. The “production” and installation of these materials often includes several modern techniques, which allow their use in construction. A number of case studies demonstrate that natural materials have a potential to reduce EE and EG. Renewable materials and/or simple production methods are the basis for these reduction potentials. Wooden structures were found to be the most beneficial in terms of reduction of EG and EE. Due to the current limited use of many local, natural materials which was previously used significantly in vernacular architecture, data on EE and EG are often lacking from databases and maybe sometimes for this reason not considered by architects.

4.2.2 *Recycled and reused materials and components*

Recycled construction materials are materials that have undergone reprocessing or renewal and can be further used in construction as a replacement for new materials. The use of recycled or reused materials compared with standard materials can reduce the EEG of buildings, particularly when the process of recycling or making materials or components ready for reusing has lower EEG than production of virgin materials. Even more beneficial for the environment is the reuse of materials or whole building components. On the other hand, recycling is an option for components which are at the end of their life - although they are unusable in their actual state, they can be transformed for another application.

Several case studies, listed in table 6 below analyse the use of recycled and reused materials in non-load bearing structures for use in new buildings. No case studies regarding the use of recycled materials for load-bearing structures were found, however, it is known that there is a possibility particularly in the construction of smaller houses. The strategy for reusing whole building structures is further discussed in section 4.3.6. Furthermore, for instance recycling of reinforcement steel is very common, as well as, the recycling of concrete and its use as an aggregate.

Table 6: Case studies illustrating how EG and EE of buildings can be reduced by using recycled or re-used materials for non-load bearing structures.

Case study	Building/ compo-nent type	Main materials (load bearing structure)	Reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
UK11	Olympic stadium	Scenario 1: Use of cement substitutes and recycled aggregate in concrete and other strategies to reduce EG of concrete	-	A1 - A3		No EG reduction by use of recycled aggregates, but 11.6 % reduction thanks to cement substitution	
		Scenario 2: baseline average scenario for concrete					
CZ1	Residential (single family)	Scenario 1: reinforced concrete columns and burned bricks, wooden ceiling and roof.	60 years	A1 - A3, B6	Benefits from reuse of materials were almost completely annulated due to necessary modifications of construction compared with reference house with the same parameters.		
		Scenario 2: cavity bricks, wooden ceiling and roof.					
KR3	Office	Slag-concrete and steel framed structure.	50 and 100 years	A1 - A5, B6, C5	Use of recyclable materials can be handed as prolongation of service life of the building and study shows that it can really significantly decrease EEG of building.		
DK2	Residential building	Scenario 1: classical materials (concrete, masonry, glass wool).	50 years	A1 - A3	For upcycle scenario material EE is 75 % lower compared with reference house.	For upcycle scenario material EG is 80% lower compared with reference house.	
		Scenario 2: Fright containers, paper wool, wood boards, paper and plastic composite materials.					
Yu & Shui, (2014)	Material testing research	Prefabricated building material with an industry by-product (fly ash) and recycled construction waste cementitious materials.					Compressive strength of the prefabricate concrete mixture of recycled cement and fly ash can reach up to 60 %
Pavlů (2015)	Recycled concrete aggregate	Scenario 1: concrete with recycled aggregate	50 years	A1-A3, C1-C4	There is no positive effect of use of recycled aggregate from C&D waste.	Positive effect of use of recycled aggregate is in recycling of concrete instead of landfilling it.	
		Scenario 2: concrete with mined gravel					

In **CZ1**, two scenarios for a single family residential building were analysed, figure 18. In the first scenario reused bricks and parts of foundations were integrated into the construction of a new house which is actually built. This scenario was compared to a reference building using approximately the same parameters in terms of size, appearance, comfort, operational energy consumption and representing a typical contemporary energy efficient residential house in local conditions. The LCA analysis however, shows that the reuse of materials has a negligible effect on reducing of the total EEG due to the additional structures needed. The walls which are built of reused bricks had to be strengthened by reinforced concrete columns and as a result, some installations could not be integrated in the walls. Thus, to hide the installations, an interior coating consisting of gypsum boards was introduced and was supported by the steel sections. Those additional structures have a high environmental impact and almost obliterate the positive effect of using reused bricks compared to reference house scenario, where new bricks are used without the necessity of strengthening and where lime plaster was used as a covering for the interior wall surfaces.

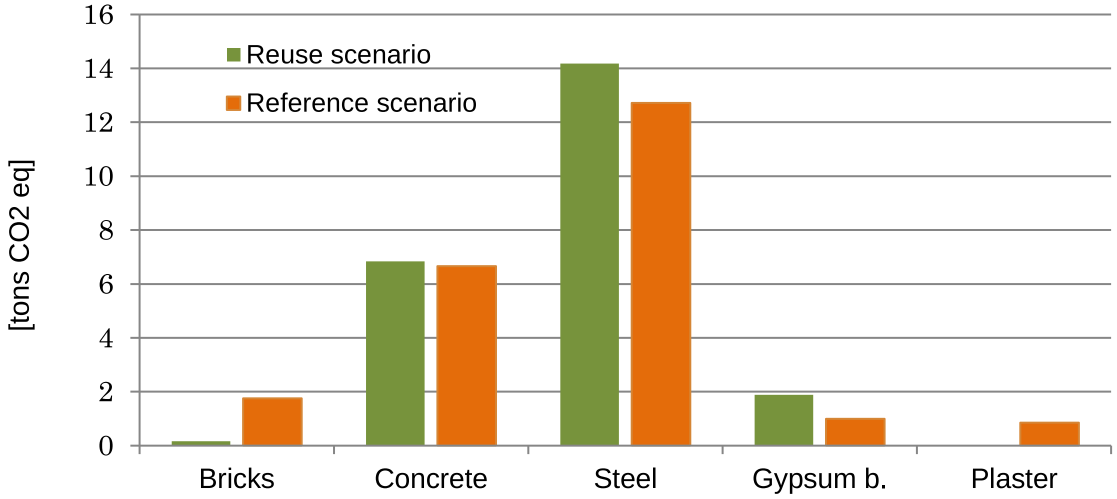


Figure 18. EG within production stage (modules A1-3) of selected materials – comparison of reuse and reference scenario (case study CZ1)

The case study **DK2** takes a more exploratory approach using a concept called “Upcycle”, where materials are recycled or reused to the greatest extent possible. A reference family house is compared to a family house of the same size and with the same construction, where the use of upcycled materials was used to the maximum, for example, 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 EE and EG of buildings could be considerably reduced, leading to a 75% reduction of EE and 80 % of EG. In this case an economic allocation of impacts from recycled materials was applied, however the way allocation is done will naturally influence the reduction potential much (see more of this discussion in section 2.6.2). However, the study also highlighted, that in order to achieve such a significant reduction of EEG, a complex and individual planning process had to be applied. Moreover, the use of large amounts of upcycled material in a building does not necessarily correspond to high reduction of environmental impacts. The accessibility, durability, production processes and applicability for the building should be taken into account and compared with a traditional material, which can be used instead where required.

The use of recycled aggregates for concrete is a very common process. The case study **UK11** and also the case study of Pavlů (2015), shows that the use of recycled aggregate has a poor effect on the reduction of EEG of the building, because aggregates contribute only to a small extent to the overall EEG of concrete. However, when construction and deconstruction waste is recycled to produce aggregates, it significantly reduces EEG of the end-of-life stage of the deconstructed buildings (4.5 Design for low impact of end-of-life stage).

The largest part of the CO_2 emissions related to concrete is caused by cement production. Thus, substitution of cement by alternatives is a good way to reduce EG. In the **UK11** case study, different measures were taken to reduce embodied impact of concrete for London Olympic Park, and substitution of cement by industrial by-products (fly ash, slag) was among the most effective – it reduced the total EG of the park by 11.6 %. In the case study of Yu & Shui (2014) substitution of cement by recycled cementitious materials from construction waste (RCWCM) and by fly ash is analysed. Results show that it is possible to replace the whole amount of cement needed by RCWCM and by fly ash, while maintaining the required mechanical requirements.

The idea of recycling and re-using of building materials is essentially a recommend approach to reduce consumption of primary raw material sources which will always be positive in terms of unwanted and unnatural changes of the landscape. However, the effect on EE or EG reduction is undetermined. There are cases when recycling or re-using reduces EE and EG of the building, but also cases when the use of recycled material can lead to an increase of embodied impacts due to, for example, a need for additional material to meet functional and/or structural requirements. The use of recycled materials often also put extra demands on the project planning process. Despite this, it is important to recognise the other benefits of reusing and/or recycling materials, such as the quality of recycled material, capability and accessibility of recycling facilities. Finally, the evidence from the case studies about the reduction potentials due to use of recycled or re-used material are still ambiguous due to ambiguities in calculation methodologies (see section 2).

4.2.3 *Innovative materials*

For the purpose of this report, innovative materials are defined as materials that are new to the construction sector and that have a potential to surpass or match the state-of-the art materials in some key parameters (technical, social, economic) whilst having lower EEG. These benefits can be reached directly at material level or at a whole building level (for example some mixtures of ultra-high performance concrete has higher environmental impacts per cubic metre than traditional concrete mixtures, but due to its higher strength enables design of more subtle structures resulting in lower environmental impacts at building level). In most cases, the impact of utilization of innovative materials needs to be assessed at the building level and all pros and cons have to be taken into account.

There are examples of material improvements from various fields that may be seen as innovative: improved mechanical properties (ultrahigh performance concrete and reinforcement materials such as steel, polymer, glass fibres or textiles); improved thermal properties (such as vacuum insulation panels, vacuum glazing units, aerogels etc.); enhanced surface treatment (new paints, nanomaterials); improved durability (such as thermally treated wood); etc. However, for the purpose of this report innovative materials with the potential of reducing building EEG are in focus, table 7.

Table 7: Case studies illustrating, how EG and EE of buildings can be reduced by using innovative materials.

Case study or source	Building/component type	Main materials	Reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
Hájek 2014	Ceiling structures	Scenario 1: reference variant – reinforced concrete slab	100 years	A1-A3, B2-B5, C1-C2	There is no reduction of EE for timber-wood composites compared to the reference variant. When only load bearing part is considered, EE is 38-53% lower for timber concrete structures.	30-45 % lower EG for timber-concrete structures compared to the reference variant. 50-65% lower EG when only load bearing part is considered.	
		Scenario 2: traditional wooden beamed ceiling					
		Scenario 3: timber-concrete composite floor structure, concrete C30/37					
		Scenario 4: timber-concrete composite floor structure, ultra-high performance concrete (UHPC)					
CZ2	Concrete frame for multi-storey building	Scenario 1: Reference monolithic reinforced concrete frame structure	100 years	A1-A3, C1-C4	About 15% lower EE for subtle HPC frame compared to reference monolithic variant	Subtle HPC frame has 20% lower EG compared to reference monolithic scenario, however only about 2% lower EG compared to precast variant.	
		Scenario 2: Precast reinforced concrete structure					
		Scenario 3: Subtle high performance concrete frame with floor panels lightened by elements from wood shavings concrete					
(Ritzen, Rovers, Lupisek, & Republic, n.d.)	Building applied and building integrated PV panels	Scenario 1: PV panels are installed on the roof as an additional structure.	20 years	A1-A3, B6	Embodied energy of building integrated PV panels is lower than that of building applied PV panels. Lower material consumption for BIPV variant has bigger influence on the EE than is lower energy output.		
		Scenario 2: PV panels are integrated in the roof structure and replace some roofing materials.					

Timber structures are used more and more frequently for multi-storey buildings. However, their inferior lateral rigidity, acoustic and fire safety parameters in comparison with concrete floor structures limit their wider application. Wooden-concrete composites may then be a suitable alternative to the timber floor structures. They typically consist of wooden beams and concrete slabs. Traditionally, the slab is made of reinforced concrete with 50 mm thickness at minimum and requires bigger dimension of beams. A very modern solution is the use of high-performance (HPC) or ultra-high performance (UHPC) concrete, which can reduce the thickness of the slab to 25 – 30 mm and thereby reduces also load bearing requirements for beams (Novotná, Fiala, & Hájek, 2013).

In a case study by Hajek et al. (2012) 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 EE and EG but has inconveniences which limits its application. The second-best is timber-concrete floor with high performance concrete, reducing EG by 44 % and EE by 10 %. Timber-concrete composite with concrete C30/37 has EG by 30 % lower but EE slightly higher than that of reinforced concrete slab. In this calculation the whole life cycle was taken into account and for three beamed variants, the non-bearing layers comprising sand and oriented strand boards (OSB) were included. The layer of OSB is supposed to be replaced twice during the life span of the floor and its impact, especially embodied energy is very high. All four floor options were also calculated only as bearing structures, without considering the sand layer and OSB decking in beamed variants. The results of this alternative calculation show, that OSBs have crucial effect on embodied energy of beamed floors. Nevertheless, these layers are necessary for maintaining acoustic requirements of beamed floor and thus, there is potential to reduce EE of timber-concrete structures by finding less energy intensive material for decking.

The case study **CZ2** displays another example of how ultra-high performance concrete (UHCP) can decrease EEG of the structure. Three different construction variants for the concrete frame structure for the multi-storey buildings are proposed (figure 19), aiming to reduce embodied impact of the entire building. The best result was achieved with the structure, where high-performance concrete was used for a structure with subtle columns and floor panels lightened by elements from wood shavings concrete. The advantage of subtle high performance concrete frame compared to the precast frame in terms of EG is very small – only about 2%. It can be assumed, that the integration of subtle elements into the building envelope of energy efficient buildings helps to avoid thermal bridges.

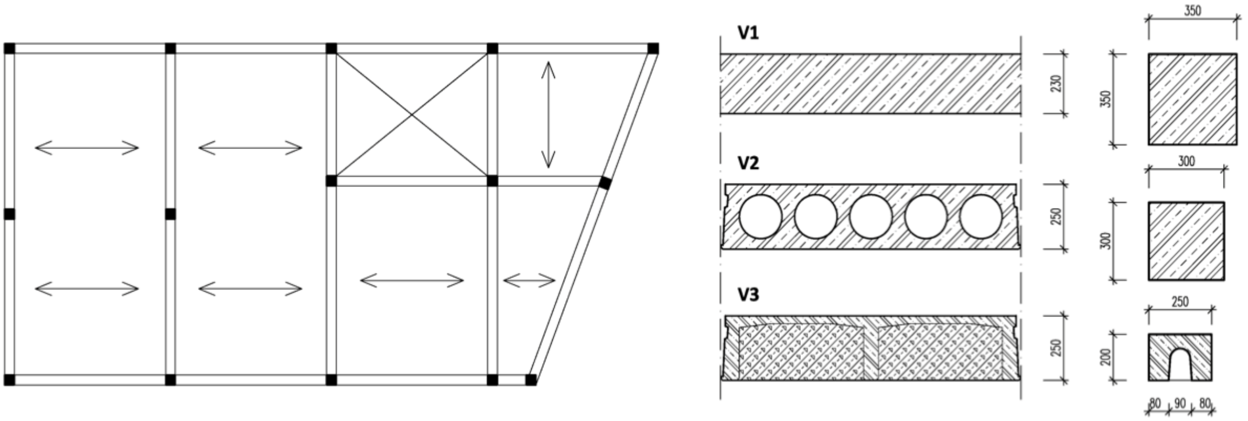


Figure 19. Three materials variants for concrete frame of multi-storey building in case study CZ2.

With the growing focus on net-zero energy and plus energy buildings, the installation of PV panels is becoming more popular. As pointed out in chapter 3.3.2, PV panels can, under some circumstances, contribute significantly to the EEG of such buildings. PV panels installed on the building rooftops and/or facades (building applied photovoltaic panels, BAPV) are most commonly installed using an additional construction added to the building envelope. This structure and the panel itself therefore increase the EE and EG of the building. Another type of PV device is called building integrated photovoltaic panels (BIPV). This type of panel is integrated into the building envelope and thus replaces roofing, façade or shading components. However, from a life cycle perspective, the different energy output efficiencies ought to be considered.

In the study of Ritzen et al. (unpublished), the EE payback of BAPV and BIPV was compared for both the Czech and Dutch climate. The BIPV saves the EE associated with the roofing materials, but have lower energy output compared with BAPV due to the limited cooling of the backside of the PV panels. The results of the study shows, that for both countries, the saving of embodied energy is due to the lower material use in the case of BIPV is larger than the negative effect of lower output of this type of panel. EE payback time is within the technical lifespan for both variants (BIPV and BAPV).

The above mentioned case studies showed a few examples of a positive effect when using some different innovative materials in the building structure in order to lower its EE and EG. This includes the use of wood-concrete composites and HSPC that can substitute structural elements in concrete, as well as building integrated PV panels which do not need additional construction elements when installed. There are, however, also examples of other materials which cause higher impacts than the ones they are substituting. On the other hand, it should be noted that due to their novelty, production methods may still be immature in relation to efficiency potentials. It can also be concluded that despite significant development in the technology in this field, there are very few published case studies that provide evidence for their potential of reducing EEG at building level.

4.3 Reduce resource use

4.3.1 *Light-weight constructions*

A 1-3	A 4-5	B 1-7	C 1-4	D
Product stage	Construction process stage	Use stage	End-of-Life	Next product system

The EE and EG related to the production of materials used in building construction makes up a large part of the total EE and EG. Section 4.2 already discussed replacing materials with others with lower EE and EG for the production stage. This often, though not always, goes together with less resource use in terms of the volume or weight used. The reduction of resource use as a strategy in this section, however, focuses on decreasing the use of a material that basically remains the same, table 8.

In a paper by De Castro et al. (2014), the EG was calculated for four external walls. All four walls, which are a typical solution for the climate in tropical Brazil, have a 25 mm exterior mineral coating and a 10 mm interior plaster coating. The walls of solid ceramic brick and concrete block walls also have a 30 mm layer of inside insulation material, while the cellular concrete block and multi-cell brick walls have an extra 5 mm interior mineral coating. Over a period of 150 years, and depending on the replacement frequency of concrete blocks and clay bricks, the use of cellular concrete and multi-cell clay leads to between 68-83% reduction in EG compared to solid concrete and clay. The influence of increasing the life time of the blocks and the brick was nevertheless larger in this study. The extension of the life time from 50 to 75 years led to an approximate reduction of 35% in EG, whereas an extension from 50 to 150 years led to around 50% reduction in EG (see section 5.3.5).

The Czech case study **CZ2** points to a reduction of approximately 10% in EE and of ca. 20% in EG from hollow core compared to solid reinforced concrete for load-bearing constructions. The calculated EG relate to material production, building construction, deconstruction, and End-of-life processes for a 6 storey house.

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Table 8: Case studies illustrating how EG and EE of buildings can be reduced by using light-weight constructions.

Case study or source	Building/component type	Main materials	Reference study period	Life cycle phases included	Observations about EE	Observations about EG
De Castro et al (2014)	External wall	Scenario 1: 110 mm concrete blocks (1700 kg/m^3)	150 years			Scenario 2 gives a 68% reduction compared to scenario 1. Scenario 4 gives a 83% reduction compared to scenario 3
		Scenario 2: 120 mm cellular concrete blocks (400 kg/m^3)				
		Scenario 3: 100 mm solid ceramic (clay) bricks (1800 kg/m^3)				
		Scenario 4: 240 mm multi-cell ceramic (clay) bricks((720 kg/m^3)				
CZ2	Concrete frame for multi-storey building	Scenario 1: Reference monolithic reinforced concrete frame structure	100 years	A1-A3, C1-C4	About 15% lower EE for subtle HPC frame compared to reference monolithic variant	Subtle HPC frame has 20% lower EG compared to reference monolithic scenario, however only about 2% lower EG compared to precast variant.
		Scenario 2: Precast reinforced concrete structure				
		Scenario 3: Subtle high performance concrete frame with floor panels lightened by elements from wood shavings concrete				
NO2	Concrete and steel frame multi-story building	Scenario 1: Reference reinforced concrete frame structure	60 years	A1-3, B1, B4	The wooden alternative structure causes 30% less weight and almost 50% less emissions	Compared to the production stage emissions, the end-of-life emissions add less than 10 % to the overall balance (8% original ZEB office case, 9% wood alternative case).
		Scenario 2: SWITCH to timber frame load bearing structure				
NO1	Timber frame, two story residential building *(Concept)*	**Concept Building** 1)Timber frame, mineral wool insulation (envelope), EPS + concrete in foundation.	60 years	A1-3, B1, B4		
NO4	Timber frame , single story, residential/demonstration building *(As built)*	**Design Drawing Stage** 2)Timber frame, mineral wool insulation (envelope), concrete in foundation, VIP used with glazing. 3)Integrated phase change material, photovoltaic panels (BAPV) integrated in sloped roof.	60 years	A1-3, A4, A5 B4		Compared to NO1 (A1-3), the 3 strip concrete foundation instead of the raft foundation led to 1/3 reduction in emissions.
		'As Built' Construction Stage 1)Omission of concrete footing between design and construction stage.				Omissions between led to over a 40% reduction in the amount of concrete used (9m3), and a 20% reduction in emissions

The Czech case study **CZ2** points to a reduction of approximately 10% in EE and of ca. 20% in EG from hollow core compared to solid reinforced concrete for load-bearing constructions. The calculated EG relate to material production, building construction, deconstruction, and End-of-life processes for a 6 storey house.

The analyses of **NO1** and **NO4** also highlight the strong reduction potential of strategies such as using a lighter, timber frame construction. The results show that certain design choices, such as a change in foundation design, can reduce EG by 21%, which could be further reduced if low EG concrete was used. **NO1** includes LCA calculations of a concept model and **NO4** calculations for an ‘as-built’ building. A comparison of **NO1** and **NO4** highlights the difference in emissions between stages of design in which LCA is carried out. For example, **NO4** is an as built project and therefore has a more detailed and comprehensive material inventory, result in higher EG. In addition, the results are higher due to more modules in the system boundary are included in the LCA calculations. In **NO1**, a raft foundation using 32m^3 was designed. By implementing a strip foundation instead, (**NO4**) led to a halving of EG due to the reduced amount of the concrete used. In addition, the concrete pier base seen in the original sketch (left in Figure 20 below) was omitted during construction, reducing the amount of concrete in the foundation even further, from 16m^3 to just 9m^3.

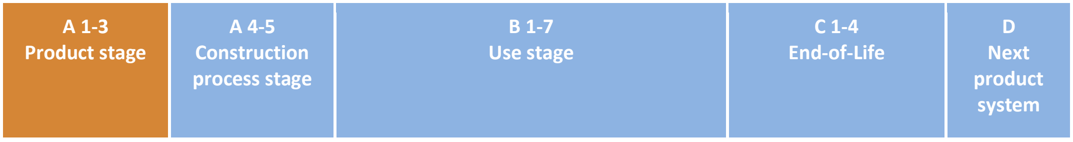
Figure 20. Details for the NO4 concrete foundation. The sketch is from the design stage (courtesy of Bergersen Arkitekter AS), and the photograph (courtesy of Marianne Rose Inman) is from the construction/as-built stage. Note the missing concrete pier foundation and additional insulation.

Although minimising concrete use in foundations has a clear environmental advantage, this should also be considered in conjunction with the material properties of the construction techniques. For example, the slab-on-ground construction technique, seen in the raft foundation of **NO1**, is technically preferable to the strip foundations with the ventilated space below, as seen 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. Although, it should be noted than the choice of the strip foundation was appropriate to the actual short lifetime of **NO4**, in that it is a demonstration building. Essentially, trade-offs need to be made between the duration of construction and concentration of embodied emissions (Inman and Houlihan Wiberg, 2015). Finally, it can be concluded that the foundation design is a fundamental design driver in reducing embodied emissions (ibid).

Finally, the substitution of structural material (as discussed in section 4.2) to wooden (i.e. lighter alternatives) also has the effect that the amount of foundation and basement materials can be reduced due to the lighter load. NO2 provides such a case in which the wooden alternative structure of the concept model caused 30% less weight and almost 50% less EG compared to the original concrete and steel ZEB office concept model.

The results of Castro et al. (2014) and of the Czech and Norwegian case studies reveal reduced resource use as a large potential strategy for reducing EEG as long as basic solidity and functional requirements are fulfilled. Examples include both the use of e.g. strip and hollow foundations as well as setting the standard for the possible weight of the structure being raised on the foundation. That is, the design of the foundation of a building has significant strategic impact on the possibilities to reduce embodied emissions of a building.

4.3.2 *Building form and design of lay-out plan*



The size of a building is also an important determinant for operational energy use, as well as, EEG. A large volume building obviously requires more EEG for construction and materials production, and usually more operational energy for indoor climate regulation and lighting, than a smaller volume building of the same construction and with the same function e.g. floor surface and number of inhabitants. It is often expected that for the same volume of building, the operational energy and EEG can be lowered by making its form more compact. The case studies collected for Annex 57 as such confirm this, but point to a limited reduction compared to, for example, material choice for building structures (table 9).

Table 9: Case studies illustrating how EG and EE of buildings can be reduced by considering building form and lay-out plans in buildings.

Case study	Building/ component type	Main scenarios studied	Reference study period	Life cycle stages included	Observations about EE	Observations about EG
SE4	Multifamily building	Six scenarios studied, Three different structural systems (concrete, solid wood, wooden frame) and two forms. Two scenarios of interest here: Rectangular form Square form	50 years	A1-3, B6		Slightly over 8% reduction with square form compared to rectangular.
SE3	Single family building	Two alternatives, concrete vs wooden structure and two internal layout designs: Original design with high volume Space-efficient internal design	50 years	A1-3, B6		No EG reduction per m^2, however more space-efficient design adds floor area – i.e. EG is reduced by 50% per person.
NO1	Single family building	Base scenario Scenario 1, option 1: Efficient internal design (reduction of floor area) Scenario 1, option 2: Internal lay-out plan to support use of passive design strategies Scenario 2: added floor area due to adding sloped roof with integrated PV	60 years	A1-3, B4, B6		Space-efficient design caused 25% reduction compared to base scenario. Lay-out plan to work with passive design strat. Only modest decrease in EG. Scenario 2 – increase in EG per m^2 due to added material (and high EG in PV)

The case study **SE4** compared EEG of two alternative forms for an early design of a Swedish multi-family building. One design had a rectangular and the other a square plan cross section. Both alternatives were studied in combination with three different building structures, i.e. solid wood, wooden frame and concrete. The EG per square meter per year for the square building (4.4 kg CO_2-eq/m^2/year for concrete structure) is clearly, but only slightly less than the EG for the rectangular one (4.8 kg CO_2eq/m^2/year) for the concrete structure. This difference, which is influenced by the building form, is far exceeded by the difference in EG between the three building structures. It can be concluded from this study that the selection of the structural materials is more important than the form of the building.

The Swedish Case study **SE3** comes to a similar conclusion. This case study evaluates a large single family house designed for four occupants, and is built according to net-zero standards for operational energy use. The design alternatives are replacement of the external reinforced concrete walls by wooden load-bearing external walls with cellulose fibre insulation, excluding a curved space on the first floor, which improves space efficiency by turning the open space as a floor area for the second floor. The reduction from excluding the curved space and turning the open volume into a floor area is far less than the reduction from replacing reinforced concrete by wooden external walls. These results relate to the per square meter floor area per year. The initial house designed for four occupants can host two additional occupants by turning the open space on the second floor into usable floor area. This design changes results in a halving of emissions EG per person per year compared to the original house designed for four people which was designed with reinforced concrete walls. The replacement of the reinforced concrete with wooden walls was found to be the second best alternative.

The Norwegian case study **NO1** also investigates the potential of building form and lay-out plan to reduce EG compared to an original 160 m^2 ZEB model. In one scenario, the building footprint is reduced from the initial 160 m^2 to 118 m^2 and two options are investigated. The first option is to keep as much as possible of the original internal layout. The second option is to organise the lay-out plan to maximize the potential of passive design strategies which involved a change in the ratio of window surface versus external wall. In a second scenario, a sloped roof is implemented which enables an increase in heated floor area from 160 m^2 to 190 m^2 by incorporating a third floor in the new roof. In the first option of the first scenario the EG per m^2 and year more or less equals the original plan. Since the floor area was reduced, however, the total emissions were reduced by 25%. Similar to the Swedish case study **SE3**, this displays the fact that a more space-efficient design can substantially reduce EG (the building serves the same function if the number of residents remains the same). In the second option of the first scenario, the changes of internal lay-out (as a consequence of optimizing the potential for passive design strategies, i.e. changing the glazing-ratio) yielded a modest decrease in EG. The total EG increased in the second scenario due to the larger floor area. However, the results show that the EG per m^2 and on an annual basis is just slightly above the reference design **NO1**. This means that the need to add function is a relevant EG reduction strategy.

All three case studies show that keeping a building as compact as possible reduces the total EG. In the Swedish examples, the reduction is moderate, however, compared to reductions obtainable by material choice. Improving the space efficiency of a building, i.e. by avoiding unnecessary open spaces and keeping floor area per person within limits, on the other hand, it can be concluded that this is a key driver for reduced emissions and is more effective than material choice for reducing total EG.

4.3.3 *Design for flexibility and adaptability*

The main rationale behind the creation of flexible/adaptable buildings/building spaces as a strategy to reduce EEG is to both extend the service life of buildings but also reduce the need for extensive material and energy use when changing building functions during its life time. Depending on the building type, added EEG due to the changing functions over the life cycle will differ. For example, building suitable for use as attractive office and retail space, tend to put high demands on frequent, and sometimes radical retrofits typically required with new tenant contracts. For example, Forsythe and Wilkinson estimate that 46-70% of the premises in a high-rise office building are retrofitted during a period of five years (Forsythe and Wilkinson, 2015). Slaughter (2001) studied a sample of 48 US buildings which showed that a building, in general, undergoes more renovations and changes than anticipated, irrespective of the building type.

Slaughter (2001) refers to three main design approaches aiming at increased flexibility; physical separation, prefabrication and overcapacity. The first one aims for physical separation of the main building systems, so that a change in one part of the building does not mean that components in the entire building need to be exchanged. Prefabrication relates to the use of prefabricated components that can easily be installed and taken away without demolishing these or other building parts. Finally, overcapacity as a strategy is typically associated with, for example, the inclusion of load-bearing elements of higher capacity than what is required for the initial function, meaning opportunities for changed functions associated with higher demands for the future. This last approach can be questioned with regard to the potential to reduce EE/EG and seem to require careful consideration in relation to the specific building, if it is to be implemented in practise.

Adaptable buildings were a topic of interest already addressed in the IEA ECBS Annex 31 work. In this work, Russell and Moffatt (2004) concluded that there is limited evidence that adaptable design approaches improves environmental performance, due to a very limited number of buildings that were intentionally designed for adaptability. The review performed for this report, reveals an unchanged situation. There is still a very limited number of studies which focus on the potential effects of adaptability in relation to EEG reduction. However, since Annex 57 is compiling a large number of case studies, EEG connected to the use stage replacements and refurbishment due to changes in user requirements or changed functions shall be included in order to explore the real potential of design approaches for flexibility and adaptability.

Section 3.2.2 displays Annex 57 case studies that include calculations for replacements resulting in a variation of 10-40% of the total EG (excluding all End-of-life processes). In general, these calculations merely include replacements of building components with a service life less than the reference study period. The Danish case study **DK3a** also includes calculations for a refurbishment scenario for a single family building due to the potential of new user requirements. These requirements include the demolition and new construction of inner walls in order to change the room distribution, change of kitchen position (demolition of wall + new wall + new flooring) and include the addition of 55 m^2 floor area. In the reference building of **DK3** (Figure 24), the refurbishment (module B5) and replacements (module B4) stage add as much as 40% or 125 kg CO_2-eq/m^2 to the total EG over the 50 year life cycle (excl. all End Of Life processes). There are also a few older studies indicating that refurbishment and replacements may stand for higher proportions of the life cycle energy and greenhouse gas emissions if considering changed use (see e.g. Cole and Kernan, 1996; Howard and Sutcliffe, 1994; Treloar et al., 1999).

Table 10: Case studies illustrating how EG and EE of buildings can be reduced by considering potentials for future adaptability and flexibility in design.

Case study	Building/ component type	Main materials	Reference study period	Life cycle phases included	Observations about EE	Observations about EG
DK3	Single family building	Reference house	50 years	A1-3, B4-5, C3-4	More than 50 % reduction in module B5 EE compared to reference building	Around 50 % reduction in module B5 EG compared to reference building
		Adaptable house with external wall elements that can easily be reused in case of expanding the housing area and an internal wall system which can easily be moved to change lay-out of rooms.				
UK8/ UK11	Stadium	Design for easy deconstruction to enable efficient change in number of seats	-	A1-3		Reduction in EG with 30 000 tons CO_2-eq compared t original design (more than 50% of this reduction is associated with flexible design measures

The Swedish case study **SE6** is a commercial office building in Stockholm in which a detailed assessment of redecoration and reconstruction due to new tenant requirements was performed. The fit-out case study took place in 2014-2015 and involved the demolition and reconstruction of the interior walls, change of floor and ceiling finishes, construction of an internal staircase, change of doors and glass walls, renovation of bathrooms, change of all kitchen equipment and change of all the ventilation and lighting. The EG for the entire fit-out project amounted to 74 kg CO_2-eq./m^2 and the total EE3 to 1.4 GJ/m^2. For the studied building, these amounts equals to 5 years for EG and 0,8 years for EE3 of OE respectively. Assuming that similar fit-outs take place every 5 or 10 years, the EE and EG associated with life time fit-outs can certainly exceed the initial EG/EE (that is EG/EE of the product and construction process stage.

The Danish case study **DK3c** concerns a 2 storey single-family house of 147 m^2 (figure 21). The building is designed for adaptation in the use stage. The design considered changed user requirements during the use stage. The building's basic function keeps the same as it is designed to be used for housing during its entire life cycle. Potential changes considered by the architects include altered room distribution, possibility to move the kitchen as well as to increasing the net housing area. Key design strategies implemented in the building include the use of external wall elements that can easily be reused in case of expanding the housing area and an internal wall system which can easily be moved to change lay-out of rooms.

Figure 21. The Adaptable House by Henning Larsen Architects – case study DK3c *[©Helene Høyer, Realdania By og Byg]*

For the case study **DK3c**, a refurbishment scenario was set up and calculated and compared with the same scenario for a reference building. The studied refurbishment scenario involves refurbishment of the inner wall (demolition + new wall), change of the kitchen position (demolition of wall + new wall + new flooring) and the addition of 55 m^2 floor area in the original design of the building. The calculations display that EG connected to module B5 (refurbishment) of the adaptable house is around 50% of the reference building. For EE, module B5 of the reference building is more than double. The main reason for the EEG of the refurbishment scenario in both cases is associated with the addition of floor area. It is also the case that for this refurbishment scenario, that the adaptable house leads to the largest reduction in EEG which is largely due to the potential for reuse of the elements in the external wall.

The case study **UK8** focuses on considerations taken early in the design process for a changed future use of the London 2012 Olympic stadium. The Olympic Games required the stadium to be constructed for 80 000 seated visitors. After the Games, however, 24 000 seats would be a more appropriately sized arena. A flexible design was therefore needed to handle these changed requirements over time. The chosen design therefore consisted of a structural frame made up of parts which were easy to deconstruct. In addition, connections were bolted to facilitate dismantling and the precast seating units were bolted to the primary steel structure rather than grouting the studs to the steel (Hartman, 2012). All in all, the reduction of EG in the final design compared to the original one was almost 30 000 tonnes CO_2-eq which is significant. A closer inspection of the results shown in the case study **UK11**, displays that a more efficient space design is responsible for more than half of this reduction in EG. However, neither **UK8** nor **UK11** give detailed evidence on the significance of the particular adaptable design approaches.

Finally, Russell and Moffatt (2004) list their recommendations on the practical use of adaptable design approaches. This includes adaptations only used for expected changes, adaptations that do not imply additional costs, as well as implementing “common-sense” principles which are known to enable a wide range of changes. In this regard, it should be noted that approaches like the ones implemented in the case study **DK3c** could be relevant as long as they do not imply additional EEG associated with the product and construction process stages, since the refurbishment scenario is not really an expected scenario. For commercial office buildings like the one studied in **SE6**, it is much more reasonable to plan for frequent changes.

Two of the Annex 57 cases studies, display reduction potentials in relation to designing for adaptability. In a Danish case, case study **DK3c**, the potential to reuse external walls when adding net floor area in a future refurbishment case led to significant reductions compared to a reference building. In the construction of the Olympic Stadium in London, adaptable design was implemented to easily reduce the number of seats after the Games and formed one part of effective design strategies that reduced the EG of the original design by 24%. Apart from these two cases, studies that evaluate the potential reduction of EEG by including design for adaptation and flexibility are still uncommon. Particularly for office buildings, the recurring EEG associated with frequent fit-outs and retrofitting may in practice exceed the stages EEG associated with the production. This implies a need for further studies to display potential EEG savings particularly with regard to the adaptable design of attractive office buildings. It is recommended to focus on adaptable design for *expected* changes. However, more open scenarios should also be considered, such as developing adaptable design for potential future user requirements for larger floor area (case study **DK3c**) can be of interest to explore, if the rest of the design is not increasing EEG associated with the product and construction process stage.

4.3.4 *Low maintenance need*

Design for low maintenance need is connected with EE/EG reduction by reducing the demand for different maintenance and activities associated with repair during the use stage. It may include the design of indoor and ambient outdoor environments that allow for a low maintenance and easily maintained surfaces with regards to, for example cleaning, grass-cutting and snow clearance. Attention on material selection for surface materials and layers may lead to reductions in maintenance needs, such as façade materials with limited maintenance requirements, lawns in need for irrigation or not, different floor materials or the size of windows. Since the design of buildings affects the durability of different components, similar aspects are also examined in the next section “service life extension”. Many EEG reduction strategies related to maintenance activities (module B2), however, are not dealt with in any of the Annex 57 case studies. The topic is not covered much in the research literature. However, two studies, both on flooring material and maintenance were found. Paulsen (2001) and Minne and Crittenden (2014) provide two different studies which explored in detail the selection of floor material and its effect on the environmental impact connected to both regular and periodic maintenance from a life cycle perspective. Paulsen´s study concluded that the periodic maintenance method in some cases generated higher CO_2 emissions than the emissions associated with the production stage of the flooring material. Minne and Crittenden (2014) on the other hand displayed that vacuuming during regular maintenance was the most significant contributor to environmental impacts due to the associated maintenance. Both studies highlight the fact that internal building design, with regard to future maintenance, may be important to consider in some cases. Nevertheless, further studies are necessary, to better understand the significance of design in different building and property components for low maintenance need. At the component level, both studies display the importance of considering use stage impacts when choosing flooring materials.

4.3.5 *Design for service life extension*

Extending the service life of buildings seems an obvious way of decreasing their EEG per service year. However, this is less straightforward, than just dividing the initial EEG by the extended service life of the building. Extending the service life of a building may require increasing the durability of the initial structure in the construction, and the replacement of components and materials as part of maintenance and renovation during the service life of the building as illustrated by the case study **JP5**.

The case study **JP4** explores the influence on EG for extending the service life of the planned library in Tokyo (Japan) from 60 to 100 years. Increasing the durability of the initial structure of the library involves increasing the durability of its reinforced concrete construction, as well as increasing its earthquake-resistant strength. Rusting of the reinforcing steel rods degrades the concrete construction, but its durability can be increased by thickening the concrete covering of the rods. The Japanese government furthermore recommends increasing earthquake resistance strength by 25 or 50% by extending the service life of buildings. The combination of both measures leads to an increased use of concrete and reinforcing rods in the range of 27% or 54% for the column, beam and foundation, and 11% for the floors and walls. The life time extension from 60 to 100 years nevertheless leads to a considerable reduction in EEG, i.e. for EE of around 35 and 30%, and for EG of around 30 and 20% reduction for 25 and 50% earthquake resistance strength respectively.
Table 11: Case studies illustrating how EG and EE of buildings can be reduced by designing for service life extension.

Case study or source	Building/ component type	Main materials	Reference study period	Life cycle stages included	Observations about EE	Observations about EG
JP4	Library building	1st scenario: Reinforced concrete construction with service life of 60 years	100 years	A1-3	30-35% reduction in second scenario, depending of earth-quake resistance strength.	20-30% reduction in second scenario depending of earth-quake resistance strength.
		2nd scenario: Reinforced concrete construction with service life of 100 years and earthquake resistance				
DK3a	Single family building	Reference house	150 years	B4-5	Approx. 50 % reduction of recurring EE compared to reference building	Approx. 50 % reduction of recurring EG compared to reference building
		Design with durable materials (bricks and tiles). Large roof overhang to protect windows and doors.				
		Wooden construction with glass cladding to protect the wood. Large roof overhang to protect windows and doors.				
DK1	Office building	Concrete construction	50 and 100 years	A1-3, B4, C3-4	89 MJ/m^{2}GFA/year for RSP 50 years compared to 60 MJ/m^{2}GFA/year for RSP 100 years	7,9 kg CO$_2$ equiv. /m^2 GFA/year for RSP 50 years compared to 4,8 kg CO$_2$ equiv. /m^2 GFA/year for RSP 100 years
SE7	Multi-family building	Concrete construction	50 and 100 years	A1-5, B4-5, C1-4		8,9 kg CO 2 equiv. /m^{2}Atemp /year for RSP 50 years compared to 5,3 kg CO 2 equiv. /m^{2}Atemp /year for RSP 100 years
Rauf and Crawford (2015)	single storey detached house.	Concrete slab floor and timber stud construction. Calculation of EE for building service lives of 1-150 years.	1-150 years	A1-3, B4-5	Significant total EE decrease up to 40 year building service life. of 40 years. Less decrease after that until increase after a 105 year service life	
De Castro et al (2014)	4 different external wall types	Comparison of EG of wall types when varying the service life from 1-150 years.	1-150 years	A1-3, B4-5		Large jumps in EG occur at the end of life of bricks and blocks, i.e. extending service life of these are important.

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 reference building. One building is built with a more traditional style using heavy-weight construction (Figure 22) and the other one is built with a more modern design with low-weight construction (Figure 23). The first example was designed using durable building materials such as bricks and tiles in the main structure. The roof was constructed with a large overhang to protect the windows and doors from weathering. The second example is a wooden construction with glass cladding to protect the wood. Also, here an overhang was used to protect weaker building components like windows. Finally, the reference building (Figure 24) is a concrete construction with an estimated service life of 120 years. All houses in the case study are constructed to comply with the requirements for the 2015 low-energy-class in the Danish Building Regulation. For both building designs, the service life of the windows are estimated to increase from 25 years to 40 years compared to the reference building, due to the protection offered by the overhang of the windows. The service life of the two buildings is estimated to be 150 years. This implies that windows in the two buildings are assumed to be replaced 3 times over the life cycle whereas in the reference building windows are estimated to be replaced 4 times. This is the main reason that the EE and EG connected with the use stage replacements are halved compared to the reference building. **DK3a-b** thus is an example of the importance of design strategies to reduce the material use over the life cycle through the selection of durable materials in the building envelope, as well as external design which tries to protect external surfaces from usual 'wear and tear' brought about by weather conditions.

Figure 22. Design for long service life – traditional style.
by Leth & Gori Architects
[©Jesper Ray, Realdania By og Byg]

Figure 23. Design for long service life – modern style.
by Arkitema Architects
[©Helene Høyer, Realdania By og Byg]

Figure 24. The reference building *[©SBi]*

Rauf and Crawford (2015) analyse the influence on EE from replacing components and materials related to extending the service life from 1 to 150 years for a 291 m3 single storey detached house. The house has a concrete slab floor and brick veneer external walls. Its structural framing is of traditional timber stud construction clad with plasterboard internally. The internal walls include ceramic tiles in wet areas, and painting of the plasterboard in all other areas. The timber framed roof has softwood trusses, and is clad with concrete roof tiles along with steel gutters, down pipes and fascia. All windows are double glazed and aluminium framed. Floor coverings for the bedrooms and main living areas are nylon carpets. All other areas have a ceramic tile floor. Rauf and Crawford (2015) calculated the annual and absolute amount of EE (divided into initial and recurrent EE) in order to provide housing for a 150 year duration, considering building service life times from 1 to 150 years and assuming the rebuilding of the same house at the end of each service life time (e.g. a service life time of 1 year corresponds to 150 times the same house). The additional recurring EE was calculated from the anticipated replacement of each individual material during the service life of the house. No materials are needed to be replaced for the building service life of 1 to 10 years. Paint and carpet are the only materials with a service life shorter than 20 years, and thus also dominate recurring EE. Total EE significantly decreases up to a building service life of 40 years. It continues to decrease with longer service lives, but at a much slower rate before increasing again after a 105 year service life of the house, when recurring EE becomes increasingly important. For service lives longer than 50 years, however, there is a relatively insignificant variation in EE given the 42% error in the calculated EE.

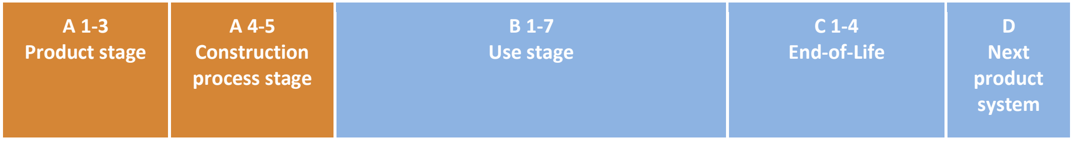
Similar to Rauf and Crawford (2015), De Castro et al. (2014) explored the influence on EG from extending the service life for buildings from 1 to 150 years, but only in relation to the different external walls. Four different walls typical for tropical Brazil were quantified, i.e. 110 mm concrete blocks, 100 mm solid ceramic (clay) bricks, 120 mm cellular concrete blocks, and 240 mm multi-cell ceramic (clay) bricks. All walls have a 25 mm mineral outside coating, and a 10 mm inside plaster coating. The walls of solid ceramic brick and concrete block walls also have a 30 mm layer of inside insulation material, while the cellular concrete block and multi-cell brick walls have an extra 5 mm inside mineral coating. In contrast to Rauf and Crawford (2015), De Castro et al. (2014) calculated the accumulated EG from 1 to 150 years, rather than on an annual basis. The results for the renovation show that the inside and outside coatings contributes to a small annual increase in EG, whilst large increases in EG occur at the end of life span of the bricks and blocks when the whole wall needs to be rebuilt. Obviously, the frequency of these increases become smaller if the life spans of the bricks and blocks are extended, and as a result the share of the bricks and blocks in EG then gets smaller. The results show that the EG from the cellular block wall is consistently lowest, and those from the solid ceramic (clay) brick wall is consistently highest. Whereas, the EG for the concrete block walls and the multi-cell ceramic (clay) bricks are almost equivalent.

Finally, the results also show that the two Annex 57 case studies **DK1** and **SE7** display how the proportional impact of module B4 increases with the increase of the reference study period. Thus, they demonstrate the importance of considering design approaches as implemented in above described **DK3a**, in particular for construction of buildings designed for a long life. In addition **DK1** concludes that the use of materials with long expected service lives of 80-100 years, such as concrete and steel, typically fall out as more advantageous in LCAs with longer reference study periods like100 years.

To conclude, it was found that extending the service life of buildings is an obvious way of decreasing EEG, as demonstrated by the case studies **DK1** and **SE7**. However, a Japanese case study **(JP5**) also shows that the design for a long building life in practice, often implies a corresponding increase in the product stage 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.

Thus from the cases and the literature studied, it can be concluded that service life extension of both the building and its components is an important strategy to reduce EEG. However, the studies also clearly show that increasing EEG in the production stage with the intention of extending the service life is not feasible if the building has a short service life. The obvious recommendation is therefore to consider this approach when it is likely that the building will last for ~ more than 50 years. It should also be noted that what is likely in different situations depends on the building function, market situation and other.

4.3.6 *Reuse of building structures*



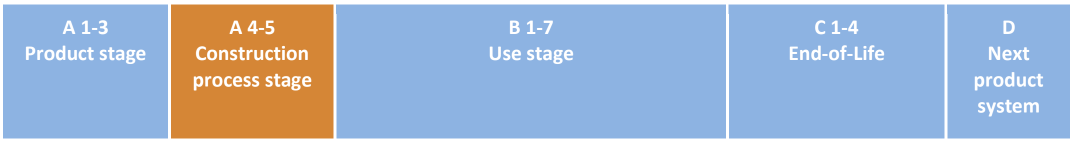
A 1-3 Product stage	A 4-5 Construction process stage	B 1-7 Use stage	C 1-4 End-of-Life	D Next product system

To reuse older building structures instead of constructing “virgin” buildings can be looked upon as a strategy to also reduce resource use and the associated EEG of the product and construction process stage. Of all the Annex 57 case studies, a number of cases focus on calculating impacts for major refurbishments. These are important in the sense that the building envelope is often more or less completely exchanged and/or the interior is completely renewed and/or replaced. Thus, the main alternative to such major refurbishments is to construct a new building on the same site. Unfortunately, none of the cases make comparisons between the EEG of a refurbishment case compared to a new-build alternative, which would have been necessary in order to discuss the reduction potentials of this strategy. However, for these relevant Annex 57 cases (see more in section 3.2.1) product stage EE ranged from around 1700-4600 MJ/m^2 (Annex 57 case studies on new build: 940-15650 MJ/m^2) and for EG 65-380 kg CO_2-eq/m^2 (Annex 57 case studies on new build: 160-640 kg CO_2-eq/m^2). These figures indicate substantial savings from reusing building structures, but are very dependent on the individual situations.

As addressed in the previous section, the case studies **DK1** and **SE7** highlight that replacing building parts (thus providing a longer building service life time) will always be advantageous compared to replacing the whole building. **SE7** also demonstrates that refurbishment to a low-energy standard will be very beneficial if looking at total greenhouse gas emissions over the life cycle, despite the addition of substantial amounts of new material.

A further opportunity for refurbishments is offered by the use of ‘smart’ façade technologies which are typically used in the design of new buildings. One example is the use of double skin façades (DSFs) which have been investigated in detail, through computer modelling, in the context of office refurbishments in the UK as an alternative to up-to-standard single skin refurbishments, see Pomponi (2015). An extensive number of configurations (2304) were assessed under the systematic variation of key design parameters, architectural choices and materials used. The EE and EG values of DSFs for refurbishments are found to be in the range of 980 – 2200 MJ/m^2 and 250 – 410 kg CO_2-eq/m^2, respectively; the main elements of variations being different structural materials and cavity widths as emerged from a sensitivity analysis. An uncertainty analysis—undertaken on the primary data collected and the whole dataset used—revealed significant coefficients of variations regarding end-of-life stages (C1 to C4 and D). Nonetheless, when embodied costs are compared against operational savings offered by DSFs over a 25-year service life, both EE and EG are easily paid back within that time for most configurations (4 and 15 years on average respectively). A broad use of DSFs for office refurbishments in the UK was thus estimated to offer net savings over 25 years in the range of 4 – 15 Mt CO2-eq depending on the scale with which this technology would be adopted in refurbishments.

4.4 Reduction of construction stage impacts



This section deals with strategies for reduction of EEG associated with the construction stage. First, the processes on site (module A5) are discussed and followed by a short note on Transport to site (module A4).

Within the A5 module it is likely to identify key reduction potentials so as to reduce the overall EEG of the building. Construction stage impacts according to EN 15978 shall involve ground works, storage of materials, any on-site transports of material, products, waste etc., supply of heating, cooling, electricity, etc. during the construction process, assembly and installation of components. Production and transports of wasted material also form part of module A5. This information gives identifies the key areas with the greatest potential for EEG reduction associated with the construction stage.

The case study **UK3** presents the emissions associated with the energy, greenhouse gas emissions, water and waste used during the construction stage of 11 housing developments in the UK based on information from the developers of these projects. The case study shows a large variation in the impact of these developments. One important variable affecting the construction stage EG is the type of energy used and whether construction takes place during the heating season. The potential correlation to other factors was also tested. However, neither project valuation nor duration of the construction was significantly correlated with the EEG connected to the construction stage of the 11 studied developments.

The Swedish case study **SE7** is only related to one case, but can be seen as a typical new-built multifamily building with concrete structure and a low-energy profile to meet the current Swedish building standard requirements. The building is constructed with pre-fabricated cement-fibre boards for the wall elements, which are used as matrices that remain in the construction and are filled with concrete on-site. Figure 25 shows construction stage impact divided on different processes for **SE7**.

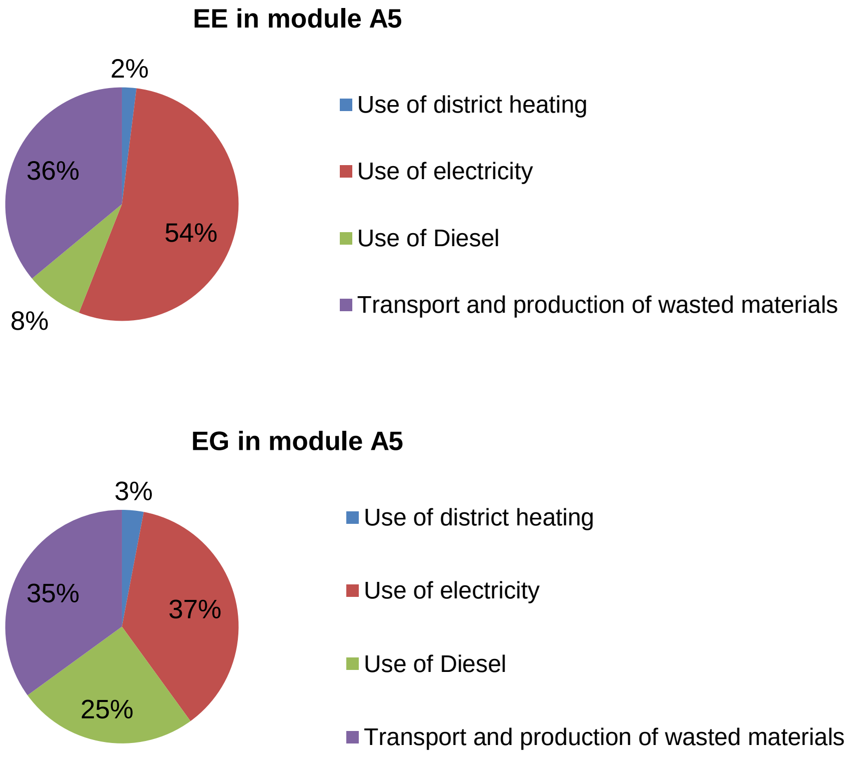


Figure 25. Processes contributing to cumulative energy demand total (upper figure) and contribution to climate change (lower figure) within module A5 in case study SE7.

Regarding the energy used in the construction stage, a number of Swedish industry case studies display potentials for reducing energy use. For example, construction sheds of higher quality which allowing for less heat loss in order to reduce heating demand, the construction sheds are heated with district heating instead of electricity, more efficient lighting is used, thus reducing the demand for drying which is met by renewable energy sources. This was found to be the most significant reduction strategies according to these Swedish studies (Hatami, 2007; Kellner and Sandberg, 2013). Kellner and Sandberg (2013) conclude that around 70 % of the electricity used on-site is associated with the lighting and heating of on-site construction sheds.

The case study **UK7** raises the issue about how different structural materials may impact the EEG emissions in module A5. Here a timber and a steel structural alternative are compared, displaying that the timber alternative requires the use of a crane and cherry-picker on-site leading to an increase in EE and EG emissions in module A5 as compared to the steel alternative (see more in section 4.2.2). If studying the full construction process stage, the steel alternative is favourable in terms of EE (but not EG), because of the higher EE for the timber alternative compared to the one in steel.

The case study **UK5** looked into the details concerning wasted material in the construction process, see figure 26. This case study includes a semi-detached house of 83 m^2 constructed with a panellised timber frame denoted “modern methods of construction” and a larch wood façade.

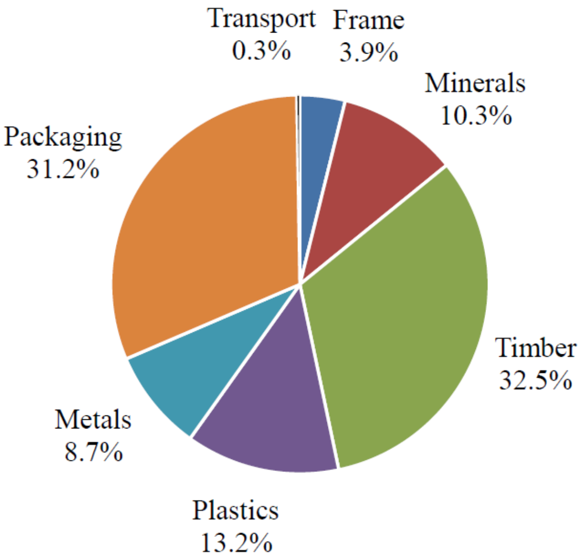


Figure 26. Proportions of different types of waste (by weight) occurring both onsite and offsite during the manufacture of the timber frame (off-site waste shown as frame category). Source: Monahan (2013)

It can be concluded from the **UK5** case study that wasted material stands for a significant share of the total EG of this building (14%) and that it totally dominates the construction stage EG. However, as illustrated in the figure above, waste associated with the pre-fabrication of the timber frame (“frame” in figure 26) was a relatively small contributor to the total waste related EG. Thus, the case study concludes that increased use of pre-fabricated components could be important to reduce waste generation associated with the construction stage.

Quale et al (2012) provides a case study which continues on the topic of pre-fabricated components, and investigates in detail the environmental impacts of conventional on-site construction compared to using modular construction for single-family buildings based on the data from three residential modular construction companies and five conventional home-builders in the US. A modular building was used as a reference and the conventional home-builders were asked to provide data for the construction of a similar building. The data collection and calculations were limited to components, materials and processes which differed between the two construction concepts.

The results of the case study by Quale et al (2012) show quite a large variation in EG between the different cases and also between the three modular options and the five conventional options. On average, the study displays a slight advantage for the modular cases when comparing the on-site energy use of the conventional homes with the energy use of the modular homes (energy use in the factories + on-site energy + energy to transport modules to site). The study also looks into transport distances to the work-place and if the associated energy use is included to account for this transport, the modular homes come out, on average, as even more favourable. One of the three modular cases, however, has quite high greenhouse gas emissions from the factory processes, due to the high electricity use and heating with oil. Quale et al (2012), as well as the case study **UK3** highlight that the location and time of the year for construction activities has an important impact on the results since it strongly impacts the heating required by the factory, as well as, the heating needed on-site.

The study by Quale et al (2012) does not, however, quantify any advantages of the modular building in relation to reduced wasted material.

Few of the Annex 57 case studies include module A4 – transport to site, however, it has been shown in the case studies that this module typically accounts for a low share of the total EE and EG. For example in **SE7**, transport to site emissions account for 3% of the total EG associated with modules A1-5. In **UK2** (retrofit case) the transport to site emissions account for 4 % of EG and 2-4% of EE. In **UK4** module A4 is more or less the same size of module A5, however both still stand for a small share of the EE and EG. Finally, in **UK5** transports to site correspond to 2% of the total EE and EG.

The study of single family homes by Quale et al (2012) shows, however, that a modular construction system implies a higher share of the EG associated to the transport of modules to site. Thus the study indicates a trade-off needs to be considered between impact in modules A4 and A5. Also, the case study by (Růžička et al. 2013) on prefabricated rammed clay panels for both load bearing and non-load bearing interior walls is an example in which transport to site emissions correspond to a high proportion of the total EG for the wall types. This is mainly due to the associated high volume and weight in combination with long transport distances to site. Kellenberger and Althaus (2008) performed a detailed LCA on a number of building components and draws the conclusion that for some components, transport to site emissions are responsible for contribution to a much higher part of the EEG of the component. The conclusions are thus not definitive but point to the fact that the transport of components and materials to the site should not be neglected in the building design and that the selection of high volumes of materials from far-reaching places certainly can have a substantial impact on the EEG. In addition, it is important to consider that in pre-fabrication there will typically be an increase of EEG in module A4, however, this can be outweighed by the larger decrease of associated emissions EEG in module A5.

Few Annex 57 case studies cover calculations of EEG associated with the construction process stage (module A5). There are also a limited amount of relevant case studies in the literature that provide more detailed studies of the processes which contribute to the impacts in these modules, as well as identifying the potentials of reduction strategies. Commonly the construction process stage corresponds to a smaller share of total EG compared to the initial and recurring impacts. However, the picture is not at all clear and there exist exceptions. With regards to module A5, the following were found to be important contributing factors; type of energy used, whether construction takes place during the heating season, energy efficiency in construction sheds and amount of wasted materials. A few studies indicate an advantage for using pre-fabricated components to reduce EE and EG associated with module A5. On the other hand, when using pre-fabricated components it becomes more important to also consider module A4 (transports to site) since the decreased EEG of module A5 may be outweighed by an increase in module A4. It is also recommended that module A4 should not be neglected in calculations by default since there exist other examples when it contributes to a substantial share of the EEG.

A final reflection is that since the product stage normally dominates the EEG in buildings, the impacts related to the construction stage are often neglected and omitted in many case studies. This is explained by the fact that very few of the Annex 57 case studies include the construction process stage in calculations, as well as limited scientific literature being available on the topic. Further detailed studies are therefore of significant importance.

4.5 Design for low impact of end-of-life stage

A 1-3 Product stage	A 4-5 Construction process stage	B 1-7 Use stage	C 1-4 End-of-Life	D Next product system

Design for recyclability is an approach, which allows for easier recycling and reuse of building materials and components at their end-of-life. This approach is closely linked to the *design for disassembly* approach, since recycling and reuse is easier in cases where the design was originally planned for easy dismantling and sorting of materials (Krumova and Crawford, 2014). The application of such an approach mostly influences the EEG in the life cycle stage module D, which lies beyond the system boundary. This module identifies the key benefits from recycling and reuse of materials which in theory can reduce the EEG in the product stage of future buildings. The use of recyclable and reusable materials can, in some cases, also positively influence the disposal stage of buildings (module C4) in the cases where the recycling or reuse of materials causes less impact than landfilling or incineration.

Table 12: Case studies illustrating, how EG and EE related to the end-of-life stages (module C) of buildings can be reduced by use of recyclable materials.

Case study	Building type	Main materials (load bearing structure)	reference study period	Life cycle phases included	Observations about EE	Observations about EG	Other observations
UK7	School	Scenario 1: steel frame, concrete blockwork infill. Scenario 2: timber panelled structure.	60 years	A1 - A5, B1 - B3, C1 - C5, D	For timbre, energy recovery potential is 56 %, for steel only 24 %.	For timbre, carbon offset potential is 44 %, for steel only 22 %.	
Junnila (2004)	15 office and residential building	Various		A1-D			

In case study **UK7**, a steel and wooden load bearing structure is compared with an emphasis on their recovery potential. The end-of-life scenario for the timber structure includes combustion with energy recovery and for carbon off-set, it was assumed that the timber would be used as a biofuel which 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 are calculated based on a methodology developed by the International Iron and Steel Institute (2002), in which credits are rewarded to steel for its recyclability potential.

The results of this case study show that recycling of steel has quite high environmental impact even though it is better than landfilling. It would be interesting to analyse the possibility of reuse of steel components, because it can significantly increase the recovery potential of steel. The study also shows the importance of material selection and waste handling. On the other hand it shows that if a designer calculates with a predicted end-of-life scenario and takes into account the recovery of materials with high EE and EG, the prediction has high uncertainty but also gives a high impact on the total environmental profile of building.

In the study of Junnila (2004), the life cycle of 15 buildings were studied and for each of them 5 different end-of-life (EoL) scenarios were taken into account. It should be noted that scenarios differed with respect to the ratio of recycled material. The first scenario considered no recycling, from the second to fourth scenario there is an increasing ratio of recycled materials and in the fifth there is maximum of reuse and recycled materials. The main conclusion is that for the scenario with a small ratio of recycling, there is no benefit from recycling and the impact is even higher than for the scenario without recycling. The reason is the transport of the material to be recycled causes a higher impact than for landfilling or incineration. On the other hand, benefits from scenarios with a higher potential for recycling and reuse significantly decreases the impacts of the whole life cycle of the building.

No case studies were found that focused on the reduction potentials of design for disassembly and reuse of components. However, since these effects are meant to support lower EEG in future buildings, the relevant case studies which highlight this issue are described in section 4.2.3. Regarding strategies for the reduction of the EEG associated with the waste treatment processes associated with the end-of-life (EoL), the case described in section 4.2.3. illustrated that recycling of a few components may increase module C EEG due to increased transport demand compared to no recycling at all. On the other hand, recycling of waste is expected to increase with current policies and with increased focus on circular economies, which implies that more consideration should be given to the selection of materials and design for future reuse and recycling.

It can be concluded that trying to reduce environmental impacts of a building's end-of-life (EoL) stage during the design stage is very difficult. It is difficult to predict further development of recycling technologies and building practice and also, even the use of buildings themselves in several decades is very unsure. However, we can assume that at least the technologies that are known today (even if not widely used) will be developed and increasingly used.

4.6 Final reflection on optimization of design

Even though EEG is becoming proportionally more important in low-energy new buildings, currently, it is still generally of less concern than operational energy use amongst industry and policy makers. Despite this, operational energy use still dominates life cycle energy use and greenhouse gas emissions of buildings, both contributing with 60 to 90% respectively to the total (Cabeza et al., 2014, Karimpour et al., 2014, Buyle et al., 2013, Yung et al., 2013, Dodoo et al., 2011, Sharma et al., 2011, Ramesh et al., 2010, Verbeeck and Hens, 2010, Sartori and Hestnes, 2007). Operational energy use will remain important in the future as well, even with worldwide implementations of low to zero energy/emission buildings. Therefore, any design or construction measures to reduce EEG should avoid increasing, and preferably rather decrease operational energy use. This is particularly relevant for the refurbishment of the large stock of existing buildings which typically accounts for a large share in the life cycle energy and greenhouse gas emissions. These measures should also be an important guiding criterion for design and construction strategies to reduce EEG in new buildings. On the other hand, minimising operational energy use should of course neither lead to an increase of EE/EG (Lützkendorf et al., 2015).

A wide range of strategies to reduce EE/EG have been discussed consecutively in this chapter. It should be noted, however, that several of these strategies are interconnected which can be considered both positive and negative. An example of a positive interrelationship can be found in De Castro et al. (2014). It is shown how a resource use can be reduced by replacing solid ceramic (clay) or concrete blocks in external walls with cellular concrete blocks or multi-cellar ceramic bricks, which leads to a (slightly) reduced need for maintenance as the cellular blocks and multi-cellar cells needs less replacement of additional coatings (De Castro, 2014). Another example of a positive interrelationship relates to the selection of (renewable) wood instead of (synthetic) concrete as a building material. Wood used for load bearing wall tends to decrease EEG (see e.g. SE4 & SE5), while operational energy use can remain the same with help of additional insulating material, even though the EEG is still less compared with concrete, as shown in for example. SE4. The resulting lighter weight for the load bearing structures are also expected to put less heavy demands on the foundation. Hence this assumes less material needed for foundation, in terms of both concrete and wood, compared to a building with heavier concrete loadbearing structures. An example of a negative interrelationship is provided by Quale et al (2012) who found that the use of pre-fabricated modules could reduce the EG related to module A5, whilst at the same time increasing the EG associated with transport to site.

Interconnections between some strategies may seem obvious but are supported by incidental case studies. There was no available literature in the field, so the findings are as a result of consistently evaluating design strategies in relation to each other, which partly is an expression of the relative young age of this field of science. It is not so easy to draw conclusions from combining findings of individual case studies, whereas, the limited number of case studies which illustrate most design and construction strategies actually also presents a challenge in drawing robust conclusions. Firstly, this is as a result of the differing methodological approaches which make them too different to compare. Secondly, differences can be found in the life cycle stages included, for example operation, and/or other stages other than material production stage only). Thirdly the results can differ according to whether or not renewable energy is included in the time spans considered which is particularly relevant for maintenance. Finally, the results differ according to which impact categories are covered e.g. only EE or EG, inclusion of both EE and EG, and whether EG includes only CO_{2eq} or also other greenhouse gases, and which performance indicators, and functional units, are used to express the results (see also Chapters 2 and 3).

Recent initiatives to standardise building assessments, as seen in EN 15978 and EN 15804, as well as recommended minimum documentation requirements as proposed by **IEA EBC Annex 57, ST1 report**, may enhance comparability of future assessments. In addition, the feasibility and EEG reduction potential of each individual design strategy is heavily influenced by a number of factors such as climate, topography, national building requirements and cultural preferences. An example of the latter is the preference for better acoustic properties of concrete over the lesser acoustic properties wood for load bearing and internal walls in the Netherlands (Pers. com. Ritzen, 2015). Construction and in particular design, is a complicated process in which many factors should be taken into account by different stakeholders at different stages of the design process. The EEG is just one of the many factors that gains in importance in the context of climate and energy policies. Design choices made early in the design process are influential in constraining possibilities for reducing EEG, as well as operational energy use and greenhouse gas emissions (OE and OG) later on. It is therefore important to involve EE/EG and OE/OG reduction considerations as early as possible in the design (and construction) process, although it is acknowledged that this is already the case for OE/OG. Including the reduction of EEG in the process is presently emerging. This chapter aims to provide a preliminary overview of the key design strategies and illustrating their potentials for reducing EG through the use of case study examples. Finally, a few of the appended cases also provided interesting examples of approaches which integrate consideration of both OG and EG into the design process. The development of the Zero Emission Building concept models (see case studies **NO1** and **NO2**) at the ZEB centre in Trondheim is one example on how different design strategies have been tested to identify concept buildings with the lowest possible total impact. In the case studies SE2b, SE4 and SE5, a basic tool, which integrates the use of sketches for use in the early design phase, is used to develop the most appropriate combination of design measures to reach a certain life cycle CO_2-eq target.

5 The influence of context on the measurement of EEG in buildings

5.1 Introduction

The previous three chapters have used the Annex 57 case studies to describe the impact of methodology and the significance of different life cycle factors (chapters 2 and 3), and some specific design and construction strategies which can reduce the embodied energy and greenhouse gas emissions of buildings (chapter 4). However at present EEG are *not* calculated, nor are they therefore reduced, in most construction projects. The existence of an accepted methodology, or of databases, or of calculation tools, has not been enough to make it happen. This chapter considers therefore how the issue can gain more attention and be included in decision-making at different levels, and to identify who is responsible for these decisions. As well as looking at intentional interventions and their impact, it also discusses some of the unintentional impacts of different contexts.

The chapter therefore broadens the discussion from the narrow focus on the technical challenges of reducing EEG, to the broader scope of examining the decision-making contexts within which those technical challenges are happening.

The chapter is structured by geographical scale. The next section briefly discusses the impact of two international initiatives in section 5.2.1, before moving on to consider the national level. Section 5.2.2 then considers the impacts of the direct interventions taken at national level to reduce EEG, including building regulations, the development of construction product EPDs and national LCA databases, and the development and use of tools to calculate EEG at building/project level. Section 5.2.3 then discusses the indirect, unintentional impacts of the different national contexts, including political, geographic, cultural and economic aspects. Section 5.2.4 considers additional regional interventions, such as planning regulations.

Section 5.3 then focuses again on intentional actions, and the unintentional influence of context, but at a project, rather than a national or regional level. It is structured in relation to the chronology of a construction project, starting with the impacts of procurement strategies, then considering the design stage, and then construction. At this level, the intentional actions are often taken by individuals or groups of individuals, and section 5.3.4 considers the roles and responsibilities of different stakeholders at each stage.

Section 5.4 summarises and draws a conclusion for the chapter.

The data analysed for this chapter comes from three sources: the collected Annex 57 case studies, the questionnaire survey of Annex 57 members in April 2015, and academic literature.

Figure 27 provides an overview of the structure of the chapter.

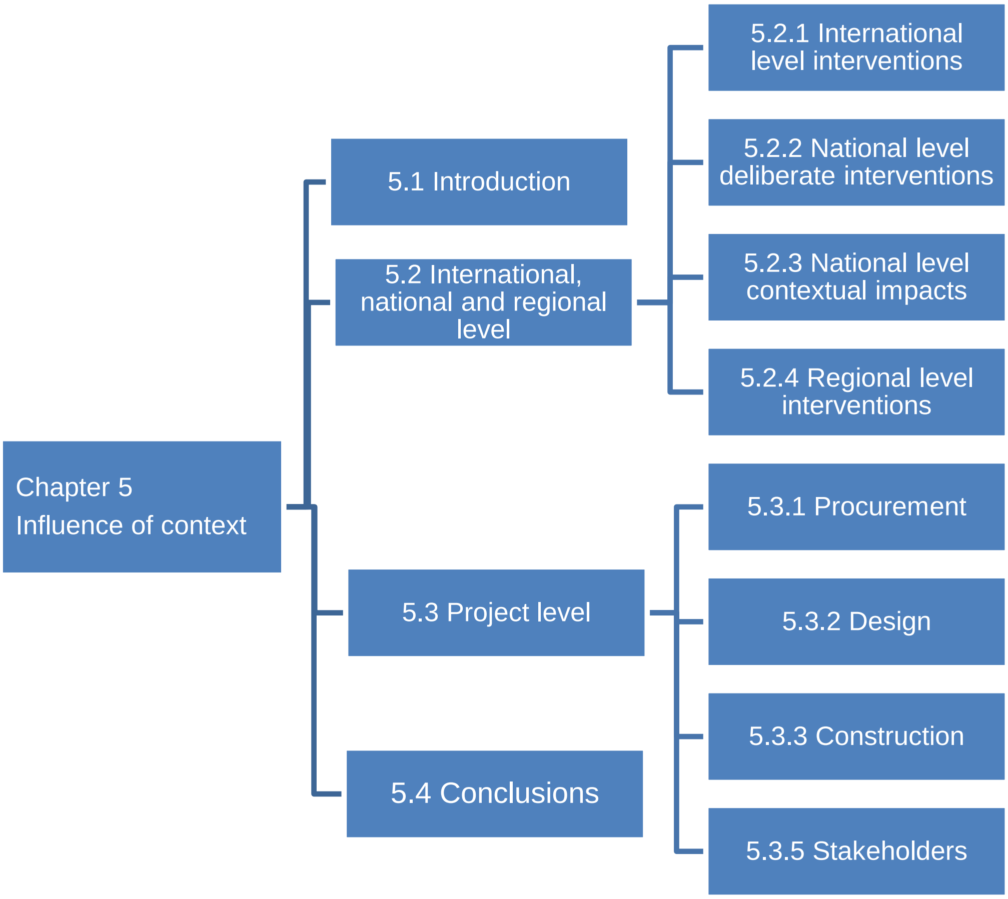


Figure 27. Content and structure of Chapter 5

5.2 International and national level

5.2.1 *International level interventions*

The impact of intentional interventions at the international level can be illustrated by the work of Annex 57 itself. As described in the **IEA EBC Annex 57, ST1 report**, experts from 15 participating countries have met and worked together over the course of the project between 2011 and 2016 to share knowledge and develop common standards and approaches. The output of the Annex 57 is a number of reports, such as this one, offering advice and recommendations based on the joint work and shared knowledge of the members. The reports will be published and shared with the IEA member Governments. Guidelines are also being written to advise and support the decisions of a range of stakeholders. Several papers have been published in international journals and at conferences, and a number more are planned for the end of the project. Thus this international project team hopes to collectively push forward understanding in the area of EEG in buildings at a pace greater than could have been achieved if each member was working individually. This understanding will also feed back to the individual work of each member, and the organisations and academic institutions to which they belong. The International Energy Agency, under whose umbrella this work is carried out, is therefore a strategic stakeholder in the international stage, and their support will make an important difference within the member countries and more widely.

The work of this Annex 57, and that of a number of initiatives nationally and internationally, has been given a rational and agreed framework through the development of the international ISO ISO/TC 59/SC 17 standards and the European TC 350 standards. Although not mandatory, these standards have set a benchmark for calculation against which national regulations can now be set, and through which clear comparative analyses of different tools and individual results can be conducted.

5.2.2 *National level interventions*

At a national level, direct impacts on the integration of EEG within construction can come from Government or from industry or non-Governmental organisations (NGO), and initiatives may be formal or informal. This section focuses on the following areas:

- the mandatory incorporation of EEG in national Building Regulations,
- the non-mandatory encouragement of EEG through certification schemes and bodies,
- the production of EPDs for construction products,
- the development of national databases,
- the development of tools to calculate EEG at a building level
- the industry initiatives

This section draws partly on research carried out by ST4 through the Venice questionnaire (described in section 1.2.4), and responses are shown in figure 28. It should be noted that while the participants have expert knowledge of the issue within their own country, they may not necessarily have a detailed knowledge of what is happening across their country. The following sub-sections consider each of the areas listed above in more detail.

Questions: These have been slightly reworded for compactness.	**Australia**	**Austria**	**Brazil**	**Czech Republic**	**Denmark**	**Finland**	**Germany**	**Italy**	**Japan**	**Republic of Korea**	**Netherlands**	**Norway**	**Spain**	**Sweden**	**Switzerland**	**UK**
Do building regulations include embodied emissions?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	~	✗	✗	✗	~	✗
Are there different requirements for domestic and non-domestic buildings?	✓	✓	✗		✗	✓	~	✓	✓	✗	✗	✓	✓	✗	~	✓
Are there sustainability certifications specific to your country?	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	~	✓	✓	✓	✓	✓
Do they include embodied emissions?	~	✗	✗	✓	✓		✓	✗	✓	✓	✓	✓		✗	✓	✓
Do other voluntary initiatives exist to measure embodied emissions?	✓	✓	✓	✓	✓	✓	✓		~	✓	✓	✓	✓	✓	✓	✓
Is there a construction LCA database for your country?	✓	✓	✗	✓	✗	~	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓
Are there (LCA) tools to calculate embodied emissions in your country?	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
Are there any on-going initiatives to develop LCA tools?	✓	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓
Is it common for construction products to have EPDs?	~	~	✗	~	~	✓	✓	~	✗	✗	✗	~	✗	✗	~	~
Is there an EPD database for your country?	~	✓	✗	✓	✓	✗	✓	✗	✓	✓	~	✓	✓	✓	~	✓
Are there any on-going initiatives to develop national databases?	✓	~	✓	✓	✗	✓	✓	~	✗	✓	✓	✓	✓	~	✓	✓

KEY:	Positive answer	✓
	Negative answer	✗
	Ambiguous/complex answer	~
	Question not answered	(blank)

Figure 28. Responses to the Annex 57 'Venice questionnaire'

Building regulations

While in some cases the integration of embodied emissions in national building regulations is encouraged, the Annex 57 countries which participated in the survey do not currently include EEG in their building regulations. The one exception is the Netherlands, where there is a mandatory calculation of material impacts; Government requires the private sector to provide product information and to use a single database and approach, but there are no set reduction targets. Plans to include the measurement of EEG in Building Regulations are currently under development in Austria and under discussion in Sweden and Denmark.

It is likely that some differences in the national context are coincidental, but others may be the result of deliberate intentions. Moncaster (2012) describes the UK Government reports which led to the development of the Building Regulations and the Code for Sustainable Homes during the first decade of the 21st Century, both of which specifically excluded embodied emissions from calculations of 'zero carbon'. Two of the reports which helped to set the landscape for the regulations, both concentrating on the need to build more homes, were written by Kate Barker (Barker, 2004) and John Callcutt (Department for Communities and Local Government, 2007b). An important policy statement emerging from the results of these two reports, 'Building a Greener Future: Towards Zero Carbon Development' (Department for Communities and Local Government, 2007a), helped to define 'zero carbon' for the next decade. In spite of responses to the consultation showing considerable demand from industry to include EG in the definition and targets, the final policy document dismissed these and specifically limited 'zero carbon' to operational impacts. Moncaster suggests that both the focus and the authors of the reports were chosen to reflect Government priorities at the time – Barker was an economist, while Callcutt was a housing developer - and therefore that the exclusion of embodied impacts from the Building Regulations was not necessarily an unconscious result of un-joined-up policy; instead it may have been hidden political agendas to encourage house building that deliberately kept this issue out of the decision-making framework.

Certification schemes

In spite of the lack of Government regulation, non-mandatory schemes have been shown to have considerable impact in changing behaviour and improving standards. Most of the Annex 57 survey participants stated that sustainability certification schemes were used in their countries. BREEAM (Building Research Establishment Environmental Assessment Methodology) was developed in the UK as a general 'design and assessment method for sustainable buildings' (http://www.breeam.org/), now used across many other countries. Germany, Austria and Denmark use the DGNB (German Sustainable Building Council) certification. LEED (originating from the US) is also widely used. Several countries have developed their own schemes, including: Green Star and NABERS (National Australian Built Environment Rating System) in Australia, Casaclima and Itaca in Italy, Selo Casa Azul in Brazil and CASBEE (Comprehensive Assessment System for Built Environment Efficiency) in Japan. Others use a combination, so for example the Netherlands uses several schemes including GPR (Green Performance of Real Estate), BREEAM and GreenCalc. In Sweden the most commonly used certification tool is Miljöbyggnad. Switzerland has a widespread labelling scheme (Minergie-Eco and Minergie-P).

The Swiss scheme requires embodied energy calculations; promoted by finance and insurance companies, who offer lower rates for certified projects, this may prove to have a strong potential to reduce embodied energy. While the Swedish Miljöbyggnad does not currently include EEG calculations as they were felt to be too complex, there is currently a discussion being held about integrating this into the tool. In addition some certification schemes, such as the HQE (High Quality Environmental) standard in France, DGNB (German Sustainable Building Council) in Germany and BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, are also linked to databases containing Environmental Product Declarations (EPDs, see section below), and the new version of LEED in the USA gives additional credits to products with EPDs. In Norway there has been an increase in the number of EPDs produced in direct response to the BREEAM requirements. Therefore the use of certification schemes can have an influence on the development and use of product-specific data. However while these certification schemes have been important in driving additional environmental issues in the construction sector, few currently require LCA calculations or specific EEG performance levels (although see section below on data for more information), and therefore in most cases participants still felt that they have not been significant drivers of reductions in embodied impacts.

Data and databases

As well as enforcement (through regulation) or encouragement (through certification schemes) of EEG measurement and reduction, it is essential that the data exists with which to do these.

On a European level, the publication of the CEN/TC 350 standards has encouraged the development of product-specific data in the form of Environmental Product Declarations (EPDs). EPDs are a method by which product manufacturers can provide verified information about the impact of a material or product on the environment. The information should be based on an LCA in accordance with the international and European standards ISO 14025:2010 and EN 15804:2012. The information includes the effects of acquiring and transporting raw materials, production energy use, content of raw materials, as well as waste and emissions generation. The calculations of EPDs are based on Product Category Rules (PCRs), which provide detailed requirements for three main aspects: hygiene, health and environment; energy economy and heat retention; sustainable use of natural resources.

Currently the production of EPDs is voluntary across all the Annex 57 countries surveyed. While most respondents reported that some EPDs had been developed, there is clearly a significant disparity between countries. At the time of writing in April 2015 a simple web search suggested that France was leading the field with 1554 EPDs, while Germany had over 500 (see figure 29). The ECO LEAF label in Japan, similar to an EPD, has also registered 430 products at time of writing.

Product manufacturers are often particularly active in promoting the creation of EPDs and even operating EPD databases and schemes. Examples include the Belgian Construction Products Producers, the Danish product associations and the RTS Building Information Foundation, involved in the EPD systems developed for Belgium, Denmark and Finland respectively. In France, the EPD system operator has been the initiative of the AIMCC, the Association of the Construction Products' Industries. Other professionals, architects and engineers, are also actively engaged in the process. One example is that of Catalonia in Spain, where CAATEB, the Association of Surveyors, Architects and Building Engineers of Barcelona oversee the EPD certification process. National research institutes and organisations are also frequently involved, such as BRE in the UK, the IVL Swedish Environmental Research Institute, and the Ministry of Construction and the Environmental Agency in Germany.

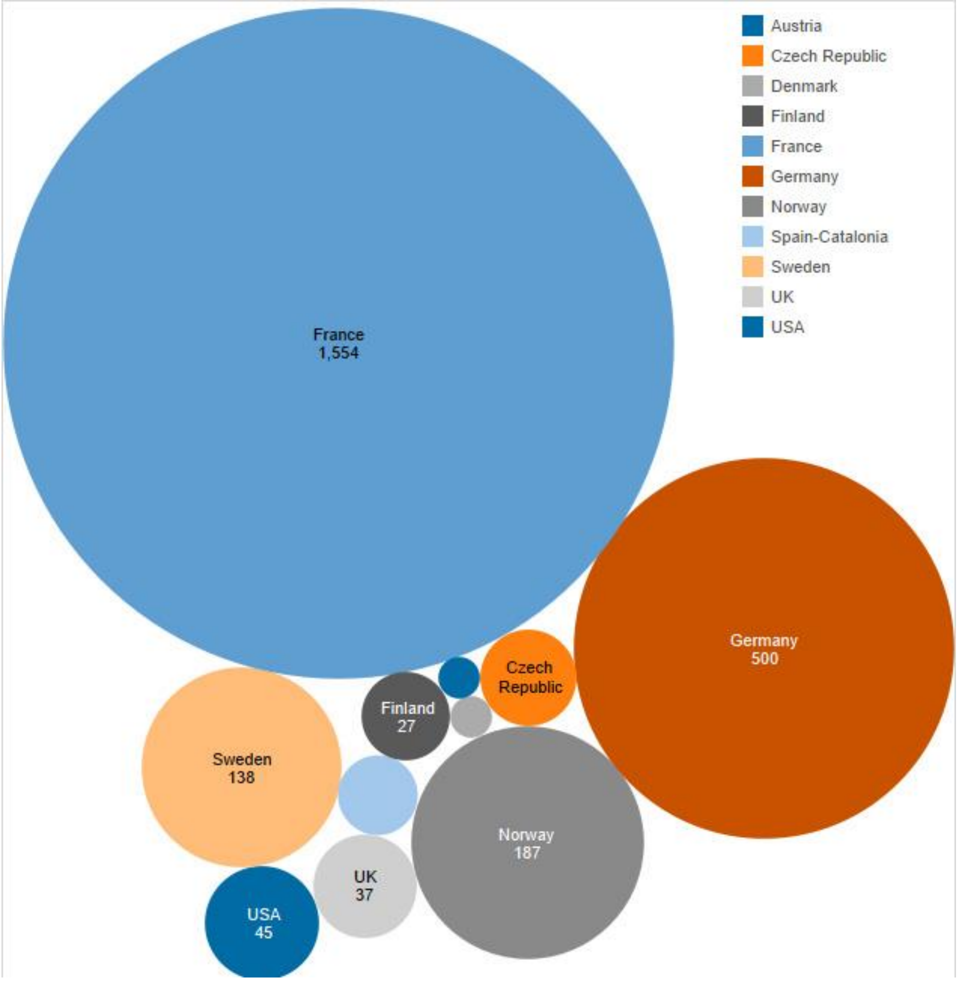


Figure 29. A 2015 snapshot of the distribution of EPDs by country.

Within many countries there is also significant data available on the EEG of generic construction materials. These are often based on average values published by different manufacturers or academic researchers. A notable early database of such information was developed by the University of Bath in the UK; the Bath Inventory of Carbon and Energy (‘Bath ICE’, Hammond and Jones 2011) is still in widespread use in the UK and elsewhere and is publically available although now out of date.

A plethora of other databases exist, containing generic or product-specific information or a mixture, and including just building products or products from all manufacturing industries. Some are in widespread use, such as Ecoinvent which is used in more than 40 countries worldwide. Austria uses Gabi, IBO and baubook. Others are country-specific, such as BRI-BEAT, developed by the Japanese Building Research Institute, and AIJ-LCA by the Architectural Institute of Japan; Envimat.cz (the Czech Republic); oekobaudat (Germany); OPENDAP (Spain); and KLCI (the Republic of Korea). As well as the Bath ICE, the UK has a database embedded within the less transparent BRE Green Guide to Specification. The Swedish Environmental Research Institute (IVL) also has its own country-specific database. However neither of these are publicly available.

Switzerland offers a free of charge LCA database tailored for the construction sector (KBOB et al. 2014a). It contains data on the manufacture and disposal of construction materials, on building technology, energy supply as well as transport services and heavily relies on the ecoinvent data (KBOB et al. 2014b). This quality controlled database allows for a consistent modelling of buildings because all data are established following the same rules, and companies are increasingly providing LCA data on their products to comply with KBOB. However this is not adapted for other countries.

The impact of these databases on the reduction of EEG is currently limited, due to a number of issues; many are a collection of generic data, which may not be accurate for a specific situation; others are collections of EPDs in a variety of formats, which are difficult to analyse; some are only available to the developing organisation, such as the BRE, or within a specific country, or at a high price; most are county-specific. There are also concerns over who should take responsibility for the databases, and for the validity and currency of their data, and so they are often left as snapshots of available data at a particular point.

Tools

Interest in reducing embodied impacts has also produced a range of software, both commercial and academic, which can be used with the material input data to calculate more or less approximate initial impacts for individual buildings. In the Netherlands, LCA tools are related to certification schemes such as GPR, BREEAM, GreenCalc, whilst in the Czech Republic, the LCA tool is included in the country's database (envimat.cz). In Australia there are numerous tools such as 'LCA Design', a BIM based LCA tool for commercial buildings and 'eTool', a web-based LCA tool for buildings. In the UK tools may be developed by academic research or engineering consultancies (Butterfly tool, Embodied Carbon Metric tool, Rapiere, LifeCYCLE), or by organisations closely connected to Government such as the Building Research Establishment (Envest, Green Guide Calculator, IMPACT) and the Environment Agency (Carbon calculator for construction projects). The Annex 57 case study **UK10** provides more details on these tools, their development and use in the UK.

Industry initiatives

As discussed, many of the tools and databases available have been developed by industry organisations, or by a combination of industry and Government, rather than solely by public bodies. In the Czech Republic, CENDEC, the Centre for Environmental Declarations, is an association of professionals promoting EPDs. Similarly, in Switzerland, technical bulletins by the Swiss Association of Engineers and Architects currently promote LCA for building construction. In the UK, the UKGBC and the Waste and Resources Action Programme (WRAP) have launched a database to capture EG data for whole buildings, aiming to encourage LCA and to help guide and inform future design and specifications. A number of major consultancies including Arup, and Aecom, conduct EG calculations with in-house tools as an additional offering to clients. A number of other small consultancies have set up business offering greenhouse gas emissions calculation in the last five years in the UK, and major clients have used these services to calculate the EG of their developments.

There are also a number of individual examples of wider initiatives designed to encourage the measurement and reduction of embodied impacts in buildings, and led by industry or industry-Government collaborations. These are starting to show a marked influence in the construction industries of specific countries.

In Denmark, Realdania Foundation is an organisation focusing on the improvement of the built environment. Realdania Byg has recently built six single-family houses (see Annex 57 case study **DK3**), in order to demonstrate different methods of reducing EG in construction. The methods included the use of recycled and upcycled building materials; the reduction of the need for frequent maintenance; the improvement of building components' precision through prefabrication; the provision of flexibility for future changes; and the contribution of occupants to GHG emissions. The sixth house combined all of the above methods. These houses illustrated how GHG emissions can be reduced during different stages of a dwelling's lifetime. While not presenting a unique solution, the project proves that GHG emissions reduction is possible and suggests methods that can be implemented in many types of constructions. The aim is to promote low emissions construction in the Danish sector and to change the ways in which designers, developers and manufacturers think and work.

In Sweden in 2014 case study **SE7** describes a new low energy multi-family building in concrete, in which whole life cycle energy use and greenhouse gas emissions (embodied plus operational) were studied in detail. The project was funded by the Swedish building industry, the Swedish government and a wide range of stakeholders from the construction industry. The results were disseminated at a seminar in June 2014 organised by the Royal Swedish Academy of Engineering Sciences and the Swedish Construction Federation, highlighting the importance of reducing embodied impacts of buildings. As a direct result of this project, the Swedish ministry for Housing commissioned the National Board of Housing, Building and Planning to investigate the life cycle of buildings, and to develop recommendations as to how to reduce climate change impacts from the Swedish building and construction sector (Boverket, 2015). The project has also created a substantial increase of interest and discussion concerning the significance of EEG in buildings, with a number of other initiatives and new R&D projects that have now followed related to the topic.

Within the UK a consortium including the UK-GBC, British Land, Derwent London, Land Securities, Tishman Speyer and WRAP ran a country-wide ‘Embodied Carbon Week’ in April 2014. Running events across the country and encouraging other companies and universities to do the same, over 900 participants from over 300 organisations attended 22 events. As well as awareness-raising, this has since sparked a number of initiatives, including the setting up of an industry Embodied Carbon Task Force. The Task Force delivered a White Paper to the UK Government calling for EG to be included as an optional method through which to demonstrate GHG emissions reduction within the next iteration of the UK Building Regulations. The Government-funding body Innovate UK has since launched a programme on ‘Building Whole Life Performance’ (February 2015), which is funding nine industry-led consortia. One consortium which includes carbon consultants, building designers, academics and the Royal Institute of Chartered Surveyors (RICS) is developing a simplified methodology and RICS-approved certification scheme for calculating EEG at early design stage.

5.2.3 *National level contextual impacts*

Sustainability in general, and the embodied impacts of buildings in particular, can be significantly influenced by the political, social, economic and geographical context.

Different countries will have both climate-related and economic reasons which exclude the use of certain materials – for example, there is no use of timber in construction in Dubai. Cultures within the construction industry will also affect both quality of workmanship, and the use of low EG materials; therefore lime-based blockwork is common in Malta but unknown in the UK. Tall buildings are becoming increasingly popular in certain cities, but not others. There is a wide variation in the availability of Government financial support for innovation across different countries. The expected life of buildings varies as widely – in the UK 80% of the existing buildings are expected to be still standing in 2050, while in Japan, where it is common to demolish buildings after 20 years life, this will be limited to buildings of historic and heritage value.

The proximity of available raw materials or manufacturing units to different areas influences the need to transport raw materials or complete products to the construction site and thus the relevant EEG. The importance of having materials available on the construction site has been highlighted by research. Morel, Mesbah, Oggero and Walker (2001), examined means to drastically reduce the environmental impact of construction and identified the establishment of an inventory of building materials available within close proximity to site as a significant stage in this process. Especially in developing countries, where labour is relatively cheap and materials’ cost can be a barrier, the availability of materials locally can be a criterion determining construction characteristics (Morel et al., 2001). Of course, the ethics of rating materials based just on their EEG is also debatable, in the context of wider environmental issues, and wider still of social and economic factors.

Research by Faulconbridge (2015) highlights the significance of local factors, including geographic and financial ones in the implementation of certification schemes and relevant decision making. Ludvig & Weiss (2013) report the difficulty of including interests from different countries when it comes to the development of standards. They suggest that developing countries, but also Eastern or Southern European ones, have limited opportunities to participate in International or European technical committees due to their limited resources, combined with the high cost of participation. Interestingly, they cite the example of national intervention which mainly occurs when national interests are affected. Austria and Finland, with big wood resources and prosperous timber industries, are more likely to have national initiatives promoting the use of timber in construction and relevant standards or legislation.

Recycling practices differ between cultures and countries, and can also have a significant effect on materials' EEG. Hammond & Jones (2011) highlight that glass recycling is difficult to apply in construction and state that glass recycling in the UK was considerably lower than that of other EU countries at time of writing.

5.2.4 *Regional level interventions*

Some examples of initiatives at a regional (sub-national) level are provided in specific case studies. Case study **UK1** focuses on the Greater London Authority (GLA) and the overt interest of the organisation in promoting EEG in the construction sector. Planning policies and decisions made within the GLA and London Boroughs are very significant, as they can influence infrastructure, developments' density, construction standards and materials and consequently energy and resources' use. A further example is found in case study **UK9**. In the UK, local planning authorities have the jurisdiction to require from new buildings a certain percentage, usually 10%, of their energy use to be provided through renewable sources (Letcher et al, 2012). In this case study of Bridport House, the use of CLT structure and the demonstration of the reduced EG compared to the previous conventional reinforced concrete frame solution was used to agree with the planning authority that a reduced level of on-site renewable energy could be provided.

5.3 Project context

Individual decisions made at a project level can have a significant contribution to the embodied impacts of the final buildings. This section is organised by the chronological stages of a project, as: procurement; design; and construction. The final sub-section also considers project-level decisions, but from the perspective of the roles that different stakeholders can have.

5.3.1 *Procurement*

The procurement process can be powerful in preventing or encouraging the introduction of EEG targets. In the case study of the Olympic Park, analysed in **UK11**, procurement enabled the use of sustainable concrete and the reduction of EG (Henson, 2011). In this project, 20% of the technical assessment was related to sustainability; this is considerably more than in conventional projects. The concrete supply was identified early as a potential risk in the Olympic Park; hence, all concrete supply was delivered by one single supplier, while a concrete batching plant was installed next to the railhead to facilitate the transport to site (Henson, 2011). The fact that there was a dedicated materials' manager within the ODA, as well as the economies of scale resulted in sustainable concrete being delivered for the whole project, with minimal costs whilst the desired aesthetical effect and structural characteristics for the buildings were achieved.

A further issue at procurement stage is the requirement of the funding body or the client for a sustainability 'badge' such as a BREAAM rating. From the professionals' perspective, additional benefits can result from working on projects badged as sustainable: they themselves gain sustainability credentials and their expertise is endorsed, leading to the award of new projects.

On a conventional project clients are often required to make decisions based on the information provided. In **UK6**, for clients to make informed decisions, the provision of comprehensible information in is crucial, although sometimes challenging. In one of the schools analysed the client considered the information too technical and overwhelming. This prevented them from an informed and smooth decision-making process.

The situation is different however in iconic projects, where the client involvement is often significant. Where sustainability is seen as an important issue targets may be set before the beginning of the project. As described in case study **UK8**, the Olympic Delivery Authority (ODA) set very challenging sustainability targets for the Olympic Park before the beginning of the project. This included operational GHG emissions reduction by 50%. Although no specific targets were set for EEG, there were high aspirations for the responsible sourcing, embodied impact and recycled content of materials, including concrete. In this large scale, iconic project, the initial aspirations of the client therefore achieved the integration of EEG in the project targets and embodied emissions' reduction in practice.

Of course economic cost is often perceived by clients to be a barrier to reducing EG as to other sustainability targets. Henson (2011) explains that in the case of the low EG concrete used in the Olympic Park, the cost of replacing aggregates with recycled material was a barrier only when not specified early. When the specifications were given to the contractors before the contract assignment, they would compete to achieve best prices in order to win the bid; hence no price premium was involved. Early and effective communication between project team members and stakeholders can contribute in achieving sustainability targets at lower costs.

Research on the role of construction materials suppliers to contribute to more sustainable buildings (Alonso et al, 2014), has demonstrated that marketing their materials through the development of LCA-based environmental information can not only improve the image of a company or brand, but also the revenue of the stakeholders and add value to company properties.

5.3.2 *Design stage*

How design teams make decisions is likely to be based on their individual specialist knowledge and experience, but also on their own values and understanding. Whose decision 'wins' will depend on the point at which they are appointed on the project, and on their professional, social and personal hierarchy within the design team.

Both for whole teams and individuals, there are clear advantages to developing specialist knowledge in low EG buildings. **UK6** describes the example of designers and contractors who, having worked with structural cross-laminated timber on a previous school building project in the UK, where it was still relatively unusual, were awarded another contract for a similar construction, due their experience. Case study **UK9** describes the collaboration of industry with researchers as having enhanced the project team's sustainability credentials, and which they expected to enable their involvement in more contracts.

On the other hand, the introduction of innovative materials and construction methods can be challenging for the professionals involved. Especially since there are no well-established practices, professionals often interpret sustainability in entirely different ways. In one of the schools analysed in **UK6** the mechanical engineer perceived sustainability as synonymous with renewable energy sources, whilst the structural engineer highlighted the importance of the EG of the structural material and proposed the use of cross-laminated timber for this reason. The quantity surveyor in turn was not keen on CLT, due to his inexperience in costing it, which might have led him to fear that his expertise would be doubted. Although in this case the character of the structural engineer was forceful enough for his arguments to win through, limited information and knowledge regarding sustainability can therefore lead to sub-optimal choices. In case study **UK4** the architect's recommendations of materials were based on the lower EG in their production stages, whilst transport, waste and demolition were ignored, thus not necessarily leading to reliable conclusions and informed decisions.

Case study **SE5** presents a holistic view on energy and materials, which includes consideration of impacts occurring before the building is constructed; this case study considers impacts rather than amounts of GHGs in kg or energy in kWh. In this sense it is a step towards life cycle thinking which may pave the way for more thorough and regularly applied LCA in the future when more life cycle data for buildings are available. **SE5** illustrates that in early design phases when many options are at hand, rough calculations often may be sufficient to indicate the consequences of different construction alternatives.

However the responsibility for reducing embodied emissions is frequently not considered at the early design stages, with most project team members perceiving this as the responsibility of sustainability consultants, who are only involved in later stages (Ariyaratne & Moncaster, (2014). This lack of relevant knowledge and responsibility among designers is further encouraged by the development of environmental certification tools which are only certified for use by specific specialist consultants. The authors note that the main constraints of EG analysis are often not the mathematical processes, but the data availability and the ease of data input, as well as commercial confidentiality issues; even when site waste and energy are monitored, which is not normal practice in most countries, contractors may be loath to share this knowledge.

Decision-making can be facilitated by tools. However some of the tools used may in fact lead to poor decisions, especially when their limitations are not taken into account; case study **UK4** shows that the tools used for EG calculations are not always transparent in their assumptions and methodologies, hence making comparisons difficult. Tools may also inadvertently influence the interpretation of sustainability, depending on the available options and the ways in which they are interpreted and presented. EE and EG can be included or not, highlighted to different levels, depending on the tools used to define sustainability on a much wider basis. In one of the schools analysed in the reference documents for **UK6**, both the structural engineer and the architect claimed that the certification tool used did not support their choice of a low EG structural material. Sustainability tools may therefore have the power to include or exclude EEG, either due to implicit biases or unintended effects.

Case study **UK4** identified the difficulty of collecting information on materials and on-site energy consumption, as well as energy data related to replacement, waste and demolition. The fact that EPDs are not currently very common (5 out of 200 products of the specific case study had EPDs) poses an additional difficulty, combined with the lack of information by manufacturers, suppliers and contractors. Another case study, **SE4**, reports that although data in accordance to ISO Standards had been requested, this could not be provided, leading to the use of reference data instead of actual. The lack of a standard methodology is a significant factor hindering EG data collection. Moreover, EG data are country specific and sources usually vary; hence databases, such as the ICE by Hammond & Jones (2011) include sources with different methodologies and system boundaries, not necessarily allowing comparisons between different materials (Knight, 2013).

5.3.3 *Construction*

UK6 also shows the potentially positive impact on contractors of developing an expertise in an innovative material. However the higher risks involved include potentially longer construction times and poor understanding of construction methods by the local workforce. For the first school to be constructed in **UK6**, an Austrian workforce was used to erect the cross-laminated timber, and their different health and safety culture created considerable concerns for the UK main contractor.

In the Olympic Park case study (**UK11**) there were extensive tests on the strength and the suitability of concrete mixes and aggregates. Clearly the project was of a far bigger scale and significance than most, and could absorb the costs of research and development, but this does show that innovations can be supported effectively in large scale projects where the clients have high aspirations. For conventional projects, this level of research needs to be funded separately to the project costs – perhaps by central Government – if innovative materials are to be encouraged.

Contractors and developers should also be encouraged in the use of low-EG materials such as CLT by the publication of their additional benefits. In case study **UK9** the change from concrete frame to CLT produced additional benefits to the design including reduced foundations, increased dimensional stability, good fire resistance, an increased airtight construction, as well as good thermal and acoustic insulation properties. The CLT construction time was only 12 weeks, as opposed to 18 weeks for the concrete structure. CLT construction is also reported by contractors interviewed after working with it for the first time as being more pleasant, clean and quiet, and with improved accessibility due to the lack of scaffolding.

5.3.4 *The role of different stakeholders*

It is clear from the preceding sections of this chapter that the context at any scale is, at least in part, set up by the actions at the level above. Thus the regulatory context, which limits or supports potential actions at project level, is based on actions which have been taken at national or international level. Different stakeholders are responsible for decisions at these different levels, as has been demonstrated in this chapter through reference to the case studies.

Part of the initial research of the IEA EBC Annex 57 group was a workshop held in 2012. The purpose of the workshop was to identify a list of stakeholders, which included:

- Manufacturers
- Contractors and builders
- Design professionals and consultants
- Investors and owners or clients
- Government, as policy-makers and regulators
- Others, including tool developers

While the workshop produced ideas about some of the questions which might be asked by these different groups about EEG (see **IEA EBC Annex 57, ST1 report**), the Venice questionnaire also attempted to identify the *responsibilities* of the different groups. Through the questionnaire participants were asked to specify which stakeholders are dominant in driving the implementation of LCA in building construction in their country; their responses are illustrated in figure 30 organised under seven groups of stakeholders: professional organisations/associations; certification schemes/organisations; academic institutions and researchers; product manufacturers and suppliers; governmental/public organisations; developers/contractors and consultancies. All respondents saw a range of stakeholders as having an impact. While the most commonly identified were government or public organisations, often related to processes like public procurement, what is interesting from this brief survey is the variety of answers. The questionnaire only asks the perspectives of the Annex 57 participants, without requiring any supporting evidence; however the answers suggest that there are a number of different actors involved in making critical decisions about EEG. No respondent saw this as the sole responsibility of Government, or as only being effected by national regulation.

	Australia	Austria	Brazil	Czech Republic	Denmark	Finland	Germany	Italy	Japan	Republic of Korea	Netherlands	Norway	Spain	Sweden	Switzerland	UK
Professional organisations/associations		✓														
Certification schemes/organisations		✓		✓	✓	✓					✓	✓				
Academic institutions, researchers				✓			✓		✓	✓		✓	✓			✓
Product manufacturers/suppliers				✓					✓							✓
Governmental/public organisations and public procurement					✓	✓	✓			✓	✓	✓	✓	✓	✓	
Developers/contractors												✓		✓	✓	
Consultancies						✓						✓			✓	✓

Figure 30. Stakeholders seen to be driving the implementation of EEG in construction in the IEA Annex 57 participating countries

5.4 Conclusions

This chapter looked at how decisions are made which might affect the EEG. An overview of the Annex 57 countries shows that there is little currently in the way of specific regulation activities to reduce EEG from buildings. However, a wide number of certification schemes, databases and tools are listed, having been developed across many of the countries. EPDs are also becoming more common, although they are currently difficult to use in analyses. The unintentional limiting factors of climate, culture and economy on the choices available include the availability and common use of different materials, the effect of climate on construction norms, and the impact of political and economic choices on building forms.

While regulation is seen as a key factor, the important role of bottom-up initiatives, often started by individual organisations or groups of construction firms, has also been demonstrated repeatedly and across different countries. Tools and databases, which often exclude new materials or contain outdated or incomparable data, are shown as both useful but also potentially limiting, as are certification schemes. Innovation needs to be supported at a high level in order to be accessible to standard-sized construction projects.

While not all issues have been discussed here, it is hoped that the inclusion of this chapter will help practitioners to understand their own potential to make a difference in the reduction of EEG from buildings. It should also explain the limitations of providing ever more accurate calculation methods and data sets, without considering the contexts within which the decisions to use these will be taken.

6 Conclusions

This report describes the research conducted by Subtask 4 (ST4) of IEA EBC Annex 57 of the International Energy Agency implementing agreement. The ST4 task was to identify and define measures to design and construct buildings with lower embodied energy and greenhouse gas emissions (EEG). In order to do this, ST4 collected and analysed around 80 case studies from the wider IEA EBC Annex 57 group. These have been collated using a template format designed by ST4 to enable transparency and accurate comparisons between cases. The full collection of the completed case study templates is included in the accompanying **IEA EBC Annex 57 ST4, Case study collection report**. Supplementary data was collected through surveys and discussions within the Annex 57, and through discrete literature reviews.

Four different levels of analysis were used to assess the impacts of methodology on the numerical results, the range and average values for impacts of different life cycle stages, components and building typologies, potential design and construction strategies for reducing EEG, and the influence of decision-making contexts on measuring and reducing EEG in buildings.

In this final chapter we summarise the conclusions from the previous four chapters, and then make some general recommendations.

6.1 Impact of methodology on numerical results

Various aspects of the methodology used in LCA studies can have an impact on the calculated values of EEG. This information is important when using these values to identify reduction strategies, as in chapter 4, because what may appear to be a useful strategy might in fact merely be the result of the chosen methodology.

There is a wide variation in the results from the case studies, and a number of areas were identified in which these variations may be due to differences in methodological choices. Key defining parameters were found to be:

- The purpose of the study.
- Reference study period for the building.
- The chronological system boundaries – for example in some studies the construction stage, and in others even the transport of workers, is included.
- The assumed future scenarios used to determine factors such as service life of materials, and end-of-life treatments.
- The level of completeness of data – whether based on drawings, BIM, or as-built information.
- The material system boundaries, or the completeness of the inventory – some case studies include mechanical and electrical services and sanitary ware, for instance.
- The LCA approach used - whether process or input-output-based.
- The source of material data - either product specific or taken from a generic database, and the assumptions made within that data such as whether carbon storage is accounted for or not.
- The choice of performance indicator, such as, whether the results are reported per gross internal floor area (GIFA) or net internal floor area (NIFA), and indeed what these terms actually cover in terms of area.

Any analyses of LCA studies should start with a detailed understanding of the methodology used, as this can have a considerable impact on the results. The first ST4 analysis identified a number of methodological impacts on the case study results. Such differences include the system boundaries – both chronological (the life cycle stages included) and physical (the completeness of the inventory), the assumed future scenarios such as for service life of materials and end-of-life treatments, the reference study period, and the LCA method used – process, input-output and hybrid approaches. These were all represented in the collected case studies. This analysis illustrates the importance of a transparent declaration of methods, system boundaries and data in building LCA studies; it is proposed therefore that the use of the ST4 template for reporting dissimilar case studies as well as the minimum data requirements proposed by Annex 57 ST1, should be adopted by academics and practitioners.

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

While a wide variation in methodological choices is demonstrated in the Annex 57 case studies, it is nevertheless possible to analyse the relative contributions to EEG from different life cycle stages, building elements and different materials within similar studies.

The EEG results presented here, illustrate how the uniqueness of not just each building but also of the unique set-up for each study reflected in the numbers. Despite these differences there are still some general trends which seem to be prevail:

- The production stage (modules A1-A3) is the life cycle stage contributing most to the EG and EE for new buildings.
- For the refurbishment cases, the replacement stage (module B4) contributes almost the same as the production stage, although this is largely dependent on the product service life.
- Technical equipment installed in the buildings may be responsible for up to 46% of the whole life EEG. However, it is noted that this is frequently excluded from assessments.
- Concrete and metals are the material types contributing the most to the EEG of the case buildings. It should be noted that concrete is often used in large amounts, for example in foundations, and that the profiling of metal can be considerably influenced by whether or not the potential recycling benefits post demolition (module D) has been included or excluded in the calculations.
- The results for timber construction is considerably affected by whether or not carbon storage is included. Either way, however, the case studies which describe using timber as an alternative structural material to concrete or steel demonstrate that the choice of timber results in lower EEG emissions.

The findings presented in this chapter suggest certain modifications in design or construction practice which could help reduce EEG from buildings. The actual design measures to potentially provide these reductions are presented in the following chapter.

The relative contributions to EEG from different life cycle stages, building elements and different materials, in studies using similar methodological approaches was considered. 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 EEG for new buildings. For refurbishment cases it was found, however, that the replacement stage (module B4) can contribute almost the same as the production stage. Technical services equipment can be responsible for a high part of the whole life EEG, although it is also frequently excluded from assessments perhaps due to a lack of data. The materials contributing the highest impacts are concrete and metals, particularly since concrete is often used in large amounts, for example in foundations. The cases which compare timber with concrete or steel demonstrate that timber is a lower EEG solution whether carbon sequestration is taken into account or not.

6.3 Strategies for the reduction of embodied energy and greenhouse gas emissions

The potential of different design and construction strategies for reduced EEG are organised under three main categories; substitution of materials, reduction of resource use and reduction of construction stage impacts. The reviewed strategies may result in reductions in any of the main life cycle stages included in the full definition of embodied impact,for example, modules A1-5, B1-5 and C1-4 and in some cases, Module D. The main conclusions from the review are listed to be:

- Natural materials: a number of case studies demonstrate that the use of natural and bio-based materials have a relatively high potential to reduce EEG, often due to the simple and low-energy production methods. However, there is limited data on EEG for traditional natural materials, and this may reduce their use in situations where this is calculated.
- Recycled and reused materials and components: While this would appear to be self-evident, the effect on EEG reduction of recycling is variable, with a few cases when the use of recycled material can lead to an increase of embodied impacts. Important influencing factors include the quality of recycled material, capability and accessibility of recycling facilities, and the potential need for additional structures and processes.
- Innovative materials: materials such as wood-concrete composites and high performance concrete have been shown to reduce EE and EG. However, in some cases such innovative materials may cause higher impacts: production methods may still be immature with future improvements in efficiency potential.
- Light-weight construction: reduced resource use has considerable potential for reducing EEG. Examples include the use of, for example, strip and hollow foundations, both of which reduce the impact of the foundations and put a limit on the weight of the building to be supported.
- Reuse of building structures: there are considerable potential EEG savings from reusing building structures rather than demolishing and rebuilding, depending on the individual context.
- Design for low end-of-life impact: Currently, there is little information on the impact of design for re-use. However, with increasing interest in policies which increase encouragement and awareness of circular economy, this is likely to become more widespread as a design strategy, and the implications for total EEG will be better understood. Predicting future waste and recycling practices remains uncertain, as do issues, such as, the longevity of the building.
- Building form and design of plan layout: While more compact building forms can reduce EEG significantly, as shown in several cases, this may lead to a limited reduction compared to material choice for building structures.
- Flexibility and adaptability: Design for adaptability may also reduce EEG in some cases, although, for most building types there is uncertainty in building in a potential strategy which may not be used. In the specific case of the Olympic Stadium in London, adaptable design was implemented to easily reduce the number of seats after the Games and formed one part of effective design strategies that reduced the EG of the original design by almost one quarter. It should be noted, however, that the EEG

associated with frequent fit-outs and retrofitting for offices, designed to be ‘flexible’ in floor plan, has a significant life cycle impact.

- Low maintenance need: There were few cases found where the need for low maintenance was reported as a specific design approach. However, as suggested above for office fit-outs, the EEG costs of future maintenance and replacement of components may be significant. Further information and research is required in this area.
- Service life extension: Extending the service life of buildings is an obvious way of decreasing EEG. Increased durability of the structure and components may have a higher initial impact, but this is likely to be considerably lower than replacing with new materials and components. However, each building should be assessed for it’s potentially for longevity depending on it’s purpose and on the context within which it is constructed.
- Reduction of construction stage impact: The few case studies which include the construction stage modules A4-5 suggest that these are a much smaller share of the total EEG compared to modules A1-3. However, there is 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. A few studies indicate that pre-fabricated components may reduce EEG in module A5, although they may conversely increase module A4 impacts (transport to site).

This theme builds upon the insights of the previous two themes to develop reduction strategies, which are discussed in chapter 4 under the following three main categories; substitution of materials, reduction of resource use and reduction of construction and end-of-life stage impacts. For the first category, a number of the case studies demonstrate that the substitution to bio-based materials will reduce EEG, due to the low-energy production methods. However the analysis of studies of recycled or innovative materials is inconclusive. The reduced use of materials, through for instance, the use of light-weight construction and reuse of old building structures, are found to be effective reduction strategies measures. The analysis also revealed that only limited studies exist which examine the impact of other strategies such as design for flexibility, adaptability and reuse. Other strategies include consideration of service life extension. This is likely to decrease EEG, since more durable components may have a higher initial impact it is likely to be considerably lower than replacing them; however each building should be assessed on the context and probable service life. Finally, while the construction stage modules A4-A5 typically contribute a smaller share of the total EEG, choices such as the energy-carrier, energy efficiency on site, site waste management, and seasonal timing of construction, can all reduce EEG.

6.4 Influence of context on the measurement of EEG in buildings

An overview of the Annex 57 countries shows that only very limited regulatory initiatives exist to reduce EEG from buildings. However, a wide number of certification schemes, databases and tools existar, having been developed across many of the countries. EPD’s are also becoming more common, although they are currently difficult to use in analyses due to a lack of conformity with regards to the calculation procedures and data sources. The unintentional limiting effects of climate, culture and economy on the choices available were also considered, as well as, others issues such as including the availability and common use of different materials, the effect of climate on construction norms, and the impact of political and economic choices on building forms.

Some key cooonclusionsare listed below:

- While regulation is seen as a key factor, and one which Governments should be encouraged to implement, the important role of bottom-up initiatives, often started by individual organisations or groups of construction firms, has also been demonstrated repeatedly and across different countries.
- Tools and databases which often are likely to exclude new materials or contain outdated or incomparable data, are shown as both useful but also potentially limiting, as are certification schemes.
- The use of innovative materials is a measure that can reduce impacts, but these need to be supported better by policy-makers in order to be accessible to small and medium-sized construction projects.

While not all contextual issues have been covered, it is hoped that the overview provided here will help building sector stakeholders to understand their own potential to make a difference in the reduction of EEG from buildings. It should also explain the limitations of providing accurate calculation methods and data sets.

This final theme discusses both the intentional and unintentional impacts on EEG reduction of national and project contexts. At a national level, there is little current regulation to reduce EEG from buildings. However a wide number of certification schemes, databases and tools have been developed. Environmental Product Declarations (EPDs) are also becoming more common, although numbers vary significantly country to country and they currently lack conformity. While regulation is seen as a key factor for the reduction of EEG, and one which Governments should be encouraged to implement, the important role of bottom-up initiatives by individual organisations or groups of construction firms has also been demonstrated, repeatedly and across different countries. Tools, databases and certification schemes are shown as both useful but also potentially limiting, through their lack of data on innovative or small-scale materials. The provision of data on innovative and low EG materials needs to be supported at a national level in order to be accessible to small and medium-sized construction projects.

6.5 Summary of recommendations

A key challenge of LCA calculations is that they can be used to produce figures for EEG, which may be misinterpreted by politicians and other decision-makers. However, as can be seen in the depth analysis produced in this report, it is clearly demonstrated that there is diversity in results which may lead to a misleading assumption that a singular methods is fundamentally flawed. To the contrary, this report has also demonstrated that as LCA methodology is becoming adopted more frequently and consistently, there are important and meaningful conclusions and recommendations that can be drawn. The potential to significantly reduce the EEG from buildings, through a wide range of different measures, has been clearly demonstrated.

The use of the case study template was, to our knowledge, a unique approach to analysing diverse data from a wide number of academic participants. The intention was never the direct comparison of results nor an attempt to develop one standard LCA method but rather to create to transparency in the different parameters that impact the final results. The collection of the case studies, and their careful analysis through four different approaches, has produced an important body of work. This will push forward the understanding both of the extent of embodied impacts of buildings, and of the methods by which we can reduce them.

As always with research, now we have reached the end of the process we also realise the limitations of what we have achieved. The next generation of case studies should use a revised template which will enable clearer and fuller comparisons. The **IEA EBC Annex 57,**

ST1 report proposes checklists and a list of minimum documentation requirements that are recommended to be followed.

The case studies and our analyses have also been limited by the data available, which is currently scarce for innovative materials and for natural and bio-based materials produced at a small-scale. We strongly recommend that the development of this data is made a priority across our nations.

From the review of design and construction strategies for low EEG in buildings, it is evident that the potential reduction potentials of strategies like flexible design, use of recycled components, low maintenance need and strategies associated with the construction stage, remains under-studied despite being key drivers for emissions reduction.

Finally, we accept that the design of a building is based on a vast range of requirements and values, of which reducing whole life cycle EEG will only ever be part. What we have shown is that the EEG are significant, and should be calculated as standard for all buildings just as in more recent years the operational impacts have been calculated.

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Guideline for designers and consultants - Part 2
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Appendices

Appendix 1: Case study details overview

Case study	Database	RSP	Product stage			Construction process stage		Use stage					End-of-Life				Next product system	Main concept	Type
			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
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	x	Refurbishment	School
CH2	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	School
CH3	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	School
CH4	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	School
CH5	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	School
CH6	EcoInvent 2.2	60	x	x	x						x				x	x	x	New	School
CH7	EcoInvent 2.2	60	x	x	x						x				x	x	x	New	School
CH8	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	Residential
CH9	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	Residential
CH10	EcoInvent 2.2	60	x	x	x						x				x	x	x	New	Residential
CH11	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	Residential
CH12	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	Residential
CH13	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurbishment	Residential
CH14	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential

			Product stage			**Construction process stage**		**Use stage**					**End-of-Life**				**Next product system**		
Case study	**Database**	**RSP**	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	**Main concept**	**Type**
CH15	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential
Czech republic																			
CZ1	Envimat	60	x	x	x													New	Residential
CZ2	Ecoinvent 2.2	100	x	x	x	x	x						x	x	x	x		-	Material
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
DK2	PE int	50	x	x	x													New	Residential
DK3a	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential
DK3b	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential
DK3c	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential
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
			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		
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
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	IO table Japan	-	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
KR4	KOR LCI	30	x	x	x						x				x	x		New	Residential
Norway																			
N01	EcoInvent	60	x	x	x						x							New	Residential
NO2	EcoInvent	60	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
			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		
NO4	EPD	60	x	x	x	x												New	Residential
NO8	EcoInvent	60	x	x	x						x							Refurbishment	Office
NO9	EcoInvent	60	x	x	x						x							New	Residential
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
SE3	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE4	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE4	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Residential
SE5	EcoEffect, BEAT, EcoInvent	50	x	x	x													New	Office
SE6	EPD, Ökobau 2013, EcoInvent, KBOB	1									x							Refurbishment	Office
SE7	IVL Miljödata, EPDs, EcoInvent, KBOB, ICE	50	x	x	x	x	x			x		x	x	x	x	x		New	Residential
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
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
UK6	-	-																-	Policy
UK7	Bath ICE	60	x	x	x	x	x		x	x			x	x	x	x	x	New	Sports hall
UK8	-	-																-	Policy
UK9	EPD, ELCD, Industry data	-	x	x	x	x	x						x	x	x	x	x	New	Residential

			Product stage			Construction process stage		Use stage					End-of-Life				Next product system		
Case study	**Database**	**RSP**	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	**Main concept**	**Type**
UK10	-	-																-	Tools
UK11	-	-																-	Policy
UK12	BATH ICE, Green guide to specification, ECEB	60	x	x	x	x	x		x	x	x	x	x	x	x	x		Refurbishment	Residential

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Energy in Buildings and
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EBC is a programme of the International Energy Agency (IEA)