EBC

Energy in Buildings and Communities Programme

International Energy Agency

Evaluation of Embodied Energy and CO_{2eq} for Building Construction (Annex 57)

Overview of Annex 57 Results

September 2016









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

iea Energy Technology Network

International Energy Agency

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Published by Institute for Building Environment and Energy Conservation,
Zenkyoren building Kojimachikan, 3-5-1, Kojimachi Chiyoda-ku, Tokyo 102-0083 Japan

ISBN (978-4-909107-10-7)

Participating countries in EBC: Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, France, Germany, Ireland, Italy, Japan, Republic of Korea, The Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States of America.

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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 (*)

Organisation and Participants

Project duration

June 2011 – November 2016

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Participating countries

Country	*Organisation*
Australia	CSIRO Land and Water
Austria	Graz University of Technology
China	Tsinghua University IKE Environmental Technology
Czech Republic	Czech Technical University in Prague
Denmark	SBi – Danish Building Research Institute
Finland	VTT Technical Research Centre of Finland
Germany	Karlsruhe Institute of Technology
Italy	IUAV University of Venice Universita degli Studi Mediterranea di Reggio Calabria University of Palermo
Japan	Kogakuin University Utsunomiya University
Korea	Korea Institute of Construction Technology
The Netherlands	Zuyd University
Norway	University of Science and Technology
Portugal	University of Minho
Spain	Spanish National Research Council CSIC
Sweden	KTH (Royal Institute of Technology) Luleå University
Switzerland	treeze Ltd. University of Applied Sciences of Western Switzerland ETH Zurich
United Kingdom	University of Cambridge
USA	Texas A&M University
Brazil (Observer)	Federal University of Esprito Santo University of Campinas

Official deliverables

Subtask 1: Basics, Actors and Concepts (Lützkendorf, Balouktsi)

Subtask 2: A Literature Review (Chae, Kim)

Subtask 3: Evaluation Methods of Embodied Energy and Embodied GHG Emissions in Building and Construction (Seo, Foliente)

Subtask 4: Case studies and recommendations for the reduction of embodied energy and embodied greenhouse gas emissions from buildings (Birgisdóttir, Houlihan Wiberg, Malmqvist, Moncaster, Nehasilova, Nygaard Rasmussen, Soulti)

Subtask 4: Case studies demonstrating Embodied Energy and Embodied Greenhouse gas Emissions in buildings (Birgisdóttir)

Project Summary Report (Seo, Zelezna, Hajek, Birgisdóttir, Nygaard Rasmussen, Passer, Lützkendorf, Balouktsi, Frischknecht, Yokoyama, Chae, Malmqvist, Houlihan Wiberg, Mistretta, Moncaster, Yokoo, Oka)

Overview of Annex 57 Results (Seo, Zelezna, Hajek, Birgisdóttir, Nygaard Rasmussen, Passer, Lützkendorf, Balouktsi, Frischknecht, Yokoyama, Chae, Malmqvist, Houlihan Wiberg, Mistretta, Moncaster, Yokoo, Oka)

Guideline for Designers and Consultants – Part 1: Basics for the Assessment of Embodied Energy and Embodied GHG Emissions (Thomas Lützkendorf, Maria Balouktsi)

Guideline for Designers and Consultants – Part 2: Strategies for Reducing Embodied Energy and Embodied GHG Emissions (Harpa Birgisdóttir and Aoife Houlihan Wiberg)

Guideline for Construction Products Manufacturers: Guidance to including Embodied Energy & Embodied GHG Emissions in the decision-making process for SME's (Alexander Passer, Maria Balouktsi, Thomas Lützkendorf, Helmuth Kreiner)

Guideline for Policy Makers (Marina Mistretta, Francesco Guarino)

Guidance to Support Educators (Petr Hajek, Julie Zelezna)

Contents

Foreword

When Annex 57 launched in preparation phase, in EBC's strategic plan for 2007-2012, it was said "LCA methods still need a great amount of research and international collaboration". The evaluation of energy consumption and related GHG emissions resulting from the use of buildings is becoming more accurate and is being applied in the design of more energy efficient building envelopes, systems and regulations. This means that the weight of the energy consumption and GHG emissions as well as GHG emission due to fluorocarbon gases caused by stages other than the use of the buildings is becoming larger, and their estimation methods will be more important in the future. It can be said that it is the time to further study the scientific basis of embodied energy and GHG emissions for building construction and new Annex 57 with international team was organized in IEA-EBC.

Embodied energy and GHG due to building construction and civil engineering account for 20% of the entire energy consumption and GHG in the world. The embodied GHG emissions due to construction industries are approximately 5 to 10% of the entire energy consumption in developed countries and 10 to 30% in developing countries. Though the rates greatly vary depending on the country and region, the reduction of embodied energy and GHG emissions may have a tremendous effect on the reduction of global energy consumption and GHG emissions.

Annex 57 research reveals the actual situation of embodied energy and GHG emissions as well as surveys their calculation methods and theoretical background. The methods and effects of reducing embodied energy and GHG emissions are shown through case studies.

Outcomes of the Annex research are compiled and finalized in a Project report and various guidelines in order to help practitioners, policy makers and other stakeholders deepen their understanding, through which a broader use of buildings with less embodied energy and GHG emissions is encouraged.

This report summarizes the different subtask reports in the Project report and the conclusions of the Annex 57 work.

Abbreviations

BIM	Building Information Modeling
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_{2eq}	CO_2 equivalent
ECCBS	Agreement on Energy Conservation in Buildings and Community Systems
EE	Embodied Energy
EEG	Embodied Energy and GHG emissions
EG	Embodied GHG emissions, Embodied CO_{2eq} emissions, Embodied CO_2 emissions
EOL	End of life
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
I-O	Input Output table
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life cycle
LCA	Life Cycle Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
NZEB	Nearly zero energy building or nearly zero emissions building
OECD	the Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ST1	Annex 57 Subtask 1 (Basics, Actors and Concepts)
ST2	Annex 57 Subtask 2 (Literature review)
ST3	Annex 57 Subtask 3 (Databases)
ST4	Annex 56 Subtask 4 (Case studies)
ZEB	Zero Energy Building
ZEH	Zero Energy House

Glossary

Term	Definition
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing.
Cradle to Site	Cradle to gate boundary plus delivery to the site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site.
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus the use stage, which includes the processes of maintenance, repair, replacements and refurbishments (production and installation of replacement products, disposal of replaced products) and the end of life stage, which includes the processes of demolition, transport, waste processing and disposal.
CO_2eq.	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so called global warming potential). [kg-CO_{2eq}]
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end of life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_{2eq} /reference unit/year of the RSP]
Greenhouse gases	They are identified in different IPCC reports
Global Warming Potential	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_{2eq} which has a GWP of 1. The time scale should be 100-year.
GFA	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output analysis	The use of national economic and energy and CO_2 data in a model to derive national average embodied energy /CO_2 data in a comprehensive framework.
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg-CO_{2eq} /unit of product or price]
Fluorocarbon	It is mainly used as the refrigerant of an air-conditioner and chiller, and a foaming agent of thermal insulation. CFC is abolished in the Montreal Protocol and HCFC will also be abolished in 2020. Fluorocarbon is shifting to HFC now. However, as for HFC, since GWP is large, reduction is called for.
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analyzed(EN15978：2011)

1. Introduction

1.1 An introduction to Annex 57 and the importance of EE and EG

Embodied energy and embodied GHG emissions (EEG) due to building construction and civil engineering account for 20% of the entire energy consumption and GHG emissions in the world. The figures are approximately 5 to 10% of the entire energy consumption in developed countries and 10 to 30% in developing countries. Though the figures greatly vary depending on the country and region, the reduction of embodied energy and GHG emissions may have a tremendous effect on the reduction of global energy consumption and GHG emissions.

Annex 57 research reveals the actual situation of embodied energy and CO_2 as well as discusses their calculation methods and theoretical background. The methods and effects of reducing embodied energy and CO_2 are shown through case studies.

In one of the former IEA EBC activities, EBC Annex 31 "Energy-Related Environmental Impact of Buildings" (1996-1999), a comprehensive overview of the theory and practice of life cycle assessment (LCA) tools of buildings, has already been presented. In EBC's strategic plan for 2007-2012, it is said that "LCA methods still need a great amount of research and international collaboration." The evaluation of energy consumption and related carbon dioxide (CO_2) emissions resulting from the use of buildings is becoming more accurate and is being applied in the design of more energy efficient building envelopes, systems and regulations. This means that the weight of the energy consumption and GHG emissions caused by stages other than the use of the buildings is becoming larger, and their estimation methods will be more important in the future. It is clearly the right time to further study the scientific basis of embodied energy and GHG emissions for building construction by organizing the new Annex and international team in IEA EBC.

The importance of embodied energy and GHG emissions is increasingly recognized; however, the current situation is that calculation conditions (prerequisite, boundary condition, etc.) and calculation methods vary greatly depending on the country or researcher, as do the results. Further, there are very few documents or guidelines covering methods for reducing embodied energy and GHG emissions. Annex 57, in cooperation with individual countries, reviews various calculation methods, and also provides a guideline for practitioners' use, in order to contribute to the reduction of embodied energy and GHG emissions.

The following specific objectives are focused on in this report.

To define the relationship between actors and targets related to embodied energy and GHG emissions for building construction (Subtask 1).

To collect and analyse existing research results concerning embodied energy and GHG emissions owing to building construction, in order to document the state of the art (Subtask 2).

To develop methods for evaluating embodied energy and GHG emissions resulting from building construction (Subtask 3).

To develop recommendations for reducing embodied energy and CO_2 in buildings, through the collection and analysis of case studies to design and construct buildings with less embodied energy and CO_2 (Subtask 4).

To develop a project summary report outlining the technical results of Annex 57 and to disseminate research results and guidelines of Annex 57 (Subtask 5)

1.2 Setting the landscape

In general, the building sector is responsible for more than 40 percent of global energy use and contributes approximately with 30% to total global Greenhouse Gas (GHG) emissions (Reference 39, 82). In efforts to reduce resource depletion and global warming, reductions in energy consumption and GHG emissions in this sector would make a significant contribution (Reference 82). Given also the high construction rates in rapidly developing nations and emerging economies being coupled with the inefficiencies of existing building stock worldwide, if nothing is done, the percentage of these contributions will likely rise further in future. Under these circumstances, intensifying the efforts for conserving the resources and reducing the adverse effects on the environment becomes increasingly important in the building sector and decision makers are called to take much more vigorous actions towards this direction than they have to date.

In the past, the attempts of the different actor groups involved in the building and construction industry to respond to the need for less resource-intensive and less polluting buildings and equipment were often focused only on reducing the operational energy consumption and the resulting GHG emissions. As significant efforts in this area continue, the accuracy of the assessment of the operational impacts (energy and GHG emissions) of buildings increases and their regulation becomes more elaborate and stringent making the design and application of more energy-efficient building envelopes and systems in new and retrofit buildings a norm in the building and real estate industry. This means that the weight of the energy consumption and GHG emissions caused by the non-operational stages of a building (from material extraction, manufacturing, construction, maintenance including repair, replacement and refurbishment, and eventual demolition and disposal) is becoming relatively larger, and thus their calculation and assessment methods will be more important in the future. Depending on the particular building in question, these impacts can range between nearly 0 per cent (e.g. Raw earth buildings) to nearly 100 per cent (e.g. nearly zero energy buildings). The average share of embodied impacts varies significantly from one country to another worldwide.

Since their consideration in every aspect of the design, construction, and use of buildings may contribute to significant reductions in resource use and environmental pollution, and therefore is regarded as critical to the implementation of sustainable development principles, they need to be understood better and assessed in a targeted manner. However, in contrast to operational impacts, embodied impacts are currently not regulated in most countries.

1.3 Why to deal with "embodied energy" and "embodied GHG emissions" today?

The growing importance of embodied energy (EE) and embodied GHG emissions (EG) has been recently recognized by various actors in the building and construction industry. However, a significant, and still considerably untapped, opportunity to limit these impacts along with the operational impacts of buildings remains. But why is the assessment and management of EE and EG of buildings much more important and urgent today than it was in the past?

a) Life cycle thinking

Over the past few years, the consideration of the full life cycle in the analysis and assessment of building solutions has prevailed worldwide. This means that subject areas traditionally focused on the stages of production and construction (e.g. the determination of costs) are now also calculated for the use phase. This has resulted, among others, in an increased application of life cycle costing (LCC) to building projects. Similarly, for topics traditionally focused on the use phase (e.g. determination of energy consumption) are now also calculated for the stages of production and construction (e.g. cumulative energy expenditure). Both trends proceeded gradually and are built on early examples dating already many decades back. However, they started being increasingly applied across the full breadth of the market in connection with the development of the sustainability discussion.

b) Increase in the ratio of embodied to operational energy and GHG emissions:

Generally, reducing the embodied energy of a building is regarded as important primarily for energy conservation reasons, as this type of energy is an integral and unavoidable part of the building's total life cycle energy use. Until recently, embodied energy assumed to be proportionally insignificant when set against the operational part of the life cycle energy. Thus, achieving operational energy savings was normally considered to be more important than reducing the embodied energy. However, the proportion of embodied energy and emissions in total life cycle depends highly on the geographic location and climate (Nebel et al., 2008).

The differences in the operational/embodied impacts ratios are significant around the world, but no comparisons can be performed, if no information is given on the building type, usage type, construction method, main building materials and energy standard, as well as if it is not clear what are the system boundaries considered in each study and what has been included in the calculation of EE or EG. This highlights the current problem that there is no generally accepted method available to calculate EE and EG accurately and consistently (Cabeza et al., 2013), and therefore, wide variations in results are inevitable (Pacheco-Torgal et al. 2013, Langston and Langston, 2008).

This ratio and its further development vary in each individual country, as it is highly influenced by the methods of construction used in each region and climate zone among others. These developments and trends are very heterogeneous - but each and every one has implications on the resource use and environmental impacts associated with the production, construction and maintenance of buildings - even in moderate climate regions with little or no heating or cooling requirements.

However, there is a global trend towards tightening up building regulations in terms of operational energy consumption, especially in climate zones with high heating and cooling energy demand. This leads the importance of EE and the associated EG to become increasingly large (Selincourt, 2012; Balouktsi and Lützkendorf, 2016). For example, EE in new, well-insulated energy efficient buildings can add up to 40% of the total energy consumption in the life cycle, and can even exceed the operational energy (Dixit et al., 2010). In addition, considering the ambition of nearly zero energy buildings by 2020 (Directive 2010/31/EU), this means theoretically that in the near future embodied energy will trend to 100%, or to nearly 100% of a building's total energy demand in Europe. Finally, the pressure to reach zero operational carbon emissions will affect adversely embodied emissions by – for example – requiring the increasing use of thermal mass and insulation as well as low and zero carbon technologies (Vukotic et.al., 2010; Selincourt, 2012).

In any case, it is clear that the importance of EE and EG increases. This is a good reason for many designers and investors, but also for legislators and standards developers to intensify the discussion on this topic.

c) Life Cycle Assessment (LCA)

The growing importance of the concept of life cycle thinking in construction industry has led to the broad application of LCA methods in practice for decision-making. LCA method usually considers damages to three "areas of protection" (AoP): human health, ecosystem and resources. The assessment of EE and EC can be considered as part of an LCA, as they are quantified by the LCA indicators assessing the use of energy resources (renewable and non-renewable) and climate changes, and thus they are linked to the AoP "resources" and "ecosystem" respectively.

d) Sustainability assessment

The last decade, there has been a shift worldwide (from predominantly qualitative approaches) to the adoption and standardization of predominantly quantitative and life cycle oriented approaches to assessing building sustainability. For example, considering the recent standards elaborated by the ISO TC 59 /SC 17 committee at an international level, and the CEN TC 350 working group at a European level, Life Cycle Assessments (LCA) are required to be performed in the course of an environmental performance assessment included in an overall sustainability assessment. In this sense, estimated values of EE can be fed into the assessment of the lifecycle use of energy resources and EG values into the assessment of the lifecycle GHG emissions (expressed in GWP) as part of an LCA, or the determination and assessment of a carbon footprint of buildings (EG is a partial carbon footprint). They therefore, being an essential piece of information, can support both a full assessment of the environmental performance of buildings and a complex evaluation of the contribution of individual buildings to sustainable development in the form of a sustainability assessment. There are already certification systems around the world considering LCA for their assessment criteria and utilizing relevant national LCI databases (Balouktsi et al., 2014).

It is clear that there are various reasons for an increased engagement with the issues of EEG; however, these contribute to a general trend towards a more intensive consideration of such topics.

1.4 A worldwide view of EE and EG

1.4.1 Worldwide Embodied GHG emissions

An estimation of the total CO_2 emissions in various countries and the corresponding fractions of embodied CO_2 emissions due to building construction and public works are shown as a result of analysis of world IO tables in Figure 1.1. In particular, fractions of embodied energy are higher in developing countries and often exceed the building operation energy. The embodied energy differs among countries depending on the level of maturity of current infrastructures (substantial expansion of infrastructures such as roads, buildings and the like or rather steady state replacements), the import and export shares of construction materials and equipment, the building design, the energy intensity of materials, and the quantity of materials used in the building.

Among the various countries, EG in China is exceptionally high, accounting for a substantial fraction of the entire CO2 emissions. Although it is certainly important to reduce the current EC, we could also consider means of greatly reducing the future EG by slightly increasing the current one. For example, we could reduce EG substantially in the future by strengthening the current building structure in order to double the durability performance.

Some of the phenomena generally observed in Asian countries include the situation in which CO_2 emissions shoot up and the fraction of EG also increases as the country becomes industrialized. Since there are many countries falling into such category, it would be effective in reducing CO_2 emissions to take appropriate measures in the initial stage of industrialization and sustain the EG reduction efforts into the future.

Embodied GHG emissions in Figure 1.1 Total CO_2 emissions in each country and the fraction of construction-related carbon shows total GHG emissions due to construction both building construction and public works which is civil engineering. The total annual GHG emissions in Japan, where the corresponding fractions of embodied CO_2 emissions due to building construction and civil engineering, and the CO_2 emissions due to building operation are estimated by the Input-Output analysis are shown in Figure 1.2. EC due to building construction is 9.5% and civil engineering, 9.7%. Total EG is 19.2% and the operation of buildings is 23.2% of the total CO_2 emissions in Japan. It is important to evaluate with not only LCA but the profile of energy consumption and CO_2 emissions at present.

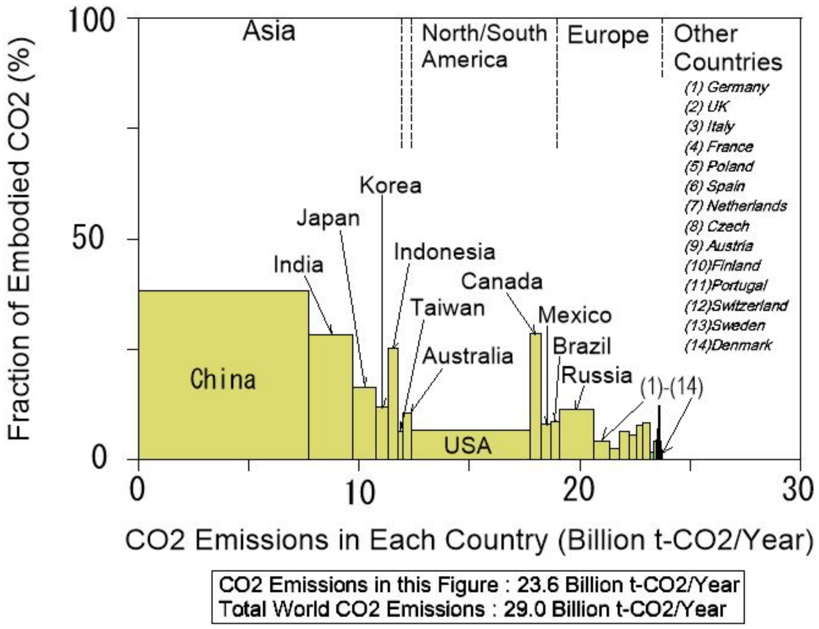
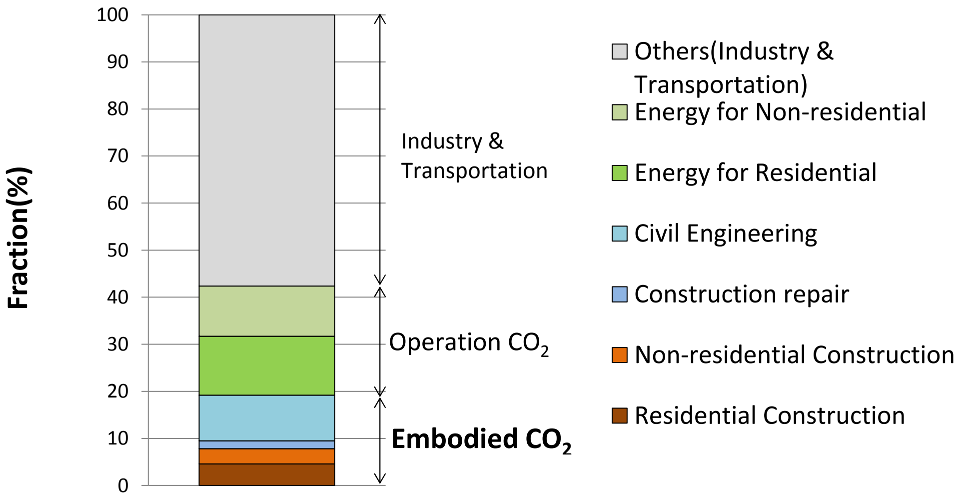


Figure 1.1 Total CO_2 emissions in each country and the fraction of construction-related carbon (Source: Oka,T, 2016)



Total CO_2 emissions in Japan, 2005: 1.29 Billion t-CO2.

Figure 1.2 Fraction of embodied CO2 due to construction in Japan, 2005 (Source: Oka,T, 2016)

1.4.2 *Average values of EEG*

(1) Materials used in buildings

There are a few countries which have statistical data about the quantity of materials used in buildings. EEG consists of the quantity of materials and EEG coefficients which depend on the industrial efficiency in the country. The quantity of materials used in buildings and coefficients of EEG in Japan is shown in this section. Table 1.1 shows average material consumptions of RC bent office in Japan classified by total floor area, in which the quantities of concrete and steel are almost same. Form work usually consumes 12 mm thick plywood in Japan.

Table 1.2 shows steel consumption of steel bent structure office in Japan. The floor is deck plate and concrete, the wall, usually lightweight concrete panel.

Table 1.1 Concrete, form work and steel per floor area of RC bent structure building in Japan

(http://www.pref.ehime.jp/070doboku/020gijutsukikak/00005739041124/gijyutu/pdf/)

Office (Bent)			Total Floor Area (m^2) =F					
Story	Material	Unit	F<200	200<F<500	500<F<1000	1000<F<2000	2000<F<3000	3000<F
2	Concrete	m^3	0.70	0.69	0.69	0.68	0.67	0.66
	Form work	m^2	8.29	7.95	7.62	7.29	6.96	6.63
	Steel	t	0.114	0.114	0.116	0.119	0.121	0.123
4	Concrete	m^3	0.68	0.67	0.66	0.66	0.65	0.64
	Form work	m^2	8.12	7.79	7.47	7.14	6.82	6.50
	Steel	t	0.125	0.125	0.128	0.130	0.133	0.135
6	Concrete	m^3	0.66	0.65	0.64	0.64	0.63	0.62
	Form work	m^2	7.95	7.63	7.32	7.00	6.68	6.36
	Steel	t	0.137	0.137	0.140	0.142	0.145	0.148

Table 1.2 Steel per floor area (m^2) of steel structure building in Japan

(http://www.pref.ehime.jp/070doboku/020gijutsukikak/00005739041124/gijyutu/pdf)

Office (Bent) : S			Total Floor Area (m^2) =F					
Story	Material	Unit	F<200	200<F<500	500<F<1000	1000<F<2000	2000<F<3000	3000<F
1	Steel	t	0.154	0.154	0.154	0.154	0.154	0.154
2			0.169	0.169	0.169	0.169	0.169	0.169
3			0.184	0.184	0.184	0.184	0.184	0.184
4			0.193	0.193	0.193	0.193	0.193	0.193
5			0.204	0.204	0.204	0.204	0.204	0.204

Floor height (FH) = 4m<FH<5m

(2) Co-efficient of EEG

Table 1.3 shows coefficients of EEG in Japan, which change according to the era and depend on the industrial efficiency in the country. Cement includes CO_2 emission from cement production which value is approximately 0.44 kg-CO_2/cement-kg. Since Japan imports whole aluminum ingot and aluminum ingot recycled is approximately 40%, the values of EEG of aluminum are low.

Table 1.4 shows the data from KBOB in Switzerland.

Table 1.3 Coefficients of EEG in Japan, 2005 (Oka, T., 2015)

Material	Embodied Energy (MJ/unit)	Embodied CO2 (kg-CO2/unit)	Unit
Log	165	11	m3
Lumber	484	1	m3
Plate glass	3947	283	t
Cement	3551	942	t
Concrete	1716	369	m3
Hot rolled steel	16989	1643	t
Air conditionner	2178	164	set
Wooden residential	3153	270	m2
Non-wooden residential	5257	489	m2
Non-wooden non-residential	4331	395	m2

Table 1.4 Excerpt of coefficients of EEG in Switzerland, 2014 (KBOB, 2014)

Construction material	Unit	Primary energy					
		Total			Non renewable		
		Total	Manufacture	End of life	Total	Herstellung	Entsorgung
		MJ oil-eq	MJ oil-eq	MJ oil-eq	MJ oil-eq	MJ oil-eq	MJ oil-eq
Timber, soft wood	kg	19.0	18.9	0.115	1.85	1.73	0.113
Glued laminated timber, soft wood	kg	34.4	34.2	0.212	8.13	7.92	0.208
2-Ⅳ glazing	m2	463	457	5.360	436	431	5.3
Concrete for construction, CEM ⅣA (Cement content 290kg/m3)	kg	0.781	0.580	0.201	0.723	0.529	0.194
Reinforcing steel	kg	13.5	13.5	0	12.7	12.7	0
Steel, beam	kg	13.3	13.3	0	12.4	12.4	0
Copper sheet	kg	39.2	39.2	0	33.2	33.2	0
Aluminum sheet	kg	143.0	143.0	0	115.0	115.0	0

Construction material	Unit	Greenhous gas emissions			End of life
		Total	Manufacture	End of life	
		kg-CO2eq	kg-CO2eq	kg-CO2eq	
Timber, soft wood	kg	0.0897	0.0805	0.00927	50% recycling and 50% incineration
Glued laminated timber, soft wood	kg	0.545	0.424	0.121	50% recycling and 50% incineration
2-Ⅳ glazing	m2	32.2	30.5	0.0105	Inert material landfill
Concrete for construction, CEM ⅣA (Cement content 290kg/m3)	kg	0.097	0.0867	0.0105	90% recycling and 10% inert material landfill
Reinforcing steel	kg	0.681	0.681	0	Recycling
Steel, beam	kg	0.733	0.733	0	Recycling
Copper sheet	kg	2.18	2.18	0	Recycling
Aluminum sheet	kg	8.25	8.25	0	Recycling

(3) EEG of buildings in Japan

Table 1.5 show the average EG values of buildings in Japan. EG due to the structure is between 40 and 60% of total EG. The building materials are more EG compared with average industrial commodities. EG due to transportation is between 12 and 17% of total EG. Transportation in Table 1.5 is from cradle to site which means total transportation in the production process of building materials.

Table 1.5 EG of buildings in Japan (Source: Oka, T., 2015)

(Unit:kg−CO2/m2)

Work item	Wooden House	SRC House	RC House	SRC Office	RC School	RC Office	Average value
Structure	113	288	324	319	313	314	185
Finish	64	105	65	136	76	86	82
HVAC and Sanitary	19	23	27	51	31	47	24
Other works	29	30	32	41	33	39	29
Transportation	48	66	63	98	81	85	59
Construction site	9	12	13	21	19	19	12
Total	286	542	544	697	579	619	405

1.5 Standards for EE and EG

Current State of Standardization

There are already various standards that can be used for “embodied energy” and “embodied CO_2 emissions” assessments. For example in Europe the voluntary standards on environmental assessment of construction products and buildings are being developed by the CEN/TC 350 committee. CEN/TC 350 is the Sustainability of Construction Works group of the European Committee for Standardization. The standards describe a harmonized methodology to assess the life cycle environmental, economic and social performance of buildings. Out of the suite of CEN TC 350 standards, the ones dealing with the description and assessment of environmental related issues for buildings and their products are shown Table 1.6.

Table 1.6 CEN TC350 standard related to the environmental assessment of and buildings and construction products

Title	Standard
EN 15643-2:2011	Sustainability of construction works - Assessment of buildings – Part 2: Framework for the assessment of environmental performance
EN 15978:2011	Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
CEN/TR 15941:2010	Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data
EN 15942:2011	Sustainability of construction works - Environmental product declarations – Communication format business-to-business
EN 15804:2012	Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products

The European standard for calculating embodied energy and embodied GHG emissions in buildings is EN 15978:2011, while EN 15804:2012 is the standard to be used for calculating the indicators at building product level. The standards developed under this framework do not set the rules for how different assessment methodologies may provide valuation methods, nor do they prescribe levels, classes or benchmarks for measuring performance.

Besides the CEN 350 series of voluntary standards, the European Union establishes the Product Environmental Footprint (PEF) recommendation, which includes reporting and benchmarking. CEN 350 standards and the PEF requirements are contradicting in several major areas such as environmental impact categories covered, as well as allocation and recycling.

In Switzerland, a technical bulletin on embodied energy and greenhouse gas emissions of building (SIA 2032) was published in 2010 as well as a technical bulletin on energy and greenhouse gas emissions benchmarks for different kinds of buildings (SIA 2040).

Internationally, the existing standards related to the environmental assessment of buildings and building products are shown in Table 1.7.

Table 1.7 Standard for the environmental assessment of buildings and products

Title	Standard
ISO 21931-1:2010	Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings
ISO 21929 -1:2011	– Building Construction Sustainability in Building Construction - Sustainability Indicators. Part 1 - Framework for the development of indicators for buildings and core indicators
ISO 21930:2007	– Sustainability in building construction - Environmental declaration of building products
ISO 14025:2006	Environmental labels and declarations - Type III environmental declarations - Principles and procedures

Other standards that can be used related specifically to carbon footprint of products are shown in Table 1.8.

Table 1.8 Standard for Carbon footprint

Title	Standard
ISO/TS 14067:2013	Carbon Footprint of Products - Requirements and guidelines for quantification and communication
Greenhouse Gas Protocol	Product life cycle accounting and reporting standard
EU Product Environmental Footprint Guide	EU Product Environmental Footprint Guide (pilot phase)

There are both international and European standards for the calculation of energy consumption and CO_2 emissions of buildings. The same applies to the provision of data and information for construction products. The standards can also be applied for determining "embodied energy" as part (or selected modules) of the cumulative primary energy consumption used to describe the use of resources, and "embodied CO_2 emissions" as part (or selected modules) of the whole life GWP (or alternatively referred to as carbon footprint in some standards). Depending on the approach and system boundaries the stages of production, construction, operation, maintenance, refurbishment and use End of Life (EOL) are included in the assessment. In particular, the uniform basis for the development and publication of environmental product declarations (EPDs) has contributed significantly to the improvement of the data availability for construction products related to "embodied energy" and "embodied CO_2 emissions". However, most EPDs do not transparently report the underlying life cycle inventory data, nor do they all apply the same modeling rules and choices. They are not consistent. That is why EPDs of different products cannot be added up to building elements nor to entire buildings.

Some countries have developed and applied their own national standards and regulations. Examples are shown in Table 1.9.

Table 1.9 National standards

Title	Country	Standard	Topic
VDI 4600	DE	Cumulative energy demand (KEA):Terms, definitions, methods of calculation (2012)	General, products
SIA 2032	CH	Grey Energy of Buildings (2010)	buildings
SIA 2040	CH	SIA Energy Efficiency Path	buildings
PAS 2050:2011 PAS 2060:2010	UK	Specification for the assessment of life cycle greenhouse gas emissions of goods and services Specification for the demonstration of carbon neutrality	general, products

1.6 EE and EG for Stakeholders

"Embodied energy" and "embodied GHG emissions" of the buildings have started attracting more and more interest from different stakeholders in different ways. For example, some local authorities have already included mandatory embodied carbon assessment as part of the planning process (Brighton and Hove City Council, 2011), designers and engineers have started looking into embodied impacts as part of LCA to develop design options (AIA, 2010), quantity surveyors are now invited to calculate embodied carbon and add this dimension to their reports (RICS, 2012), construction product manufacturers both in EU and internationally are increasingly requested to develop Environmental Product Declarations EPDs (ISO 14025:2006, EN 15804:2012) or life cycle inventory data (KBOB 2014) and to communicate them to purchasers, or to communicate the carbon footprint of construction products (ISO/TS 14067:2013). Developers and investors are interested in understanding the trade-offs between "embodied energy" and operational energy, as well as in the decision as to whether to refurbish or newly build a building.

Thus, the practical application of this new aspect is partially facilitated by a new stream of various publications in the form of guidelines specific to different building-industry stakeholder groups.

2. State of Art of EE and EG study and its application

2.1 Trend of EE and EG study

Existing research results concerning embodied energy and GHG emissions owing to building construction were collected and were analyzed and summarized them into the state of the art. Approximately 250 literature sources were selected and analyzed according to their relation with building and construction sector for the purpose of this study.

2.1.1 Research trends by year

(1) Before the year 2000

Only a few papers studying on buildings' embodied energy and its impact were found in the 1990's. Some papers tried to study methodological comparisons between Embodied Energy analysis and Emergy analysis, which is a quantitative analysis technique for determining the values of resources, services, and commodities (Brown et al, 1996). Primary energy and GHGs' embodiments in goods and service in Austria was analyzed using I-O LCA method (Lenzen, 1998). Also, there were several attempts to analyze energy and GHGs associated with building materials or construction activities.

(2) 2000 ~ 2006

By the year 2006, embodied energy and GHG emissions studies had been published at a slight but gradually increasing rate. Research themes, however, were diversified after the 2000's, though the topics were still focused on energy consumption. At building level, the subjects were building materials, structure, envelope, and energy-related installation, such as BIPV or low-energy building technology. On the national or industrial level, several papers studied energy consumption and GHG emissions impacts from the socio-economic point of view in order to be used for political decisions. The dominant methodologies were I-O LCA and hybrid LCA to analyze the embodied impacts not only in building-level, but also in national-level study. In a few studies and selected countries, process-based LCA was applied for evaluating embodied energy and GHG emissions at building level. Interestingly, a calculation framework to estimate energy footprints was suggested according to the primary energies embodied in the goods and services consumed by a defined human population (Ferng, 2002).

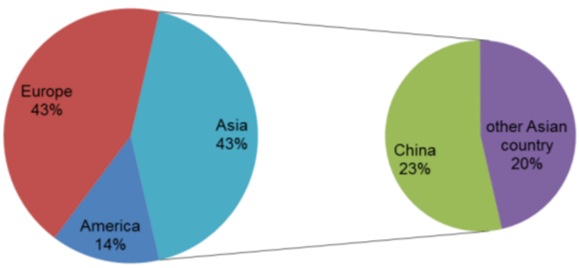
(3) After the year 2007

There was an explosive increase in the embodied energy and GHG emissions research from 2007. The methodological diversity has been found in every level of research. More studies have utilized process-based LCA methodology than before. Other special methodologies have been suggested, such as multi-region I-O LCA (Wiedman, 2007), Environmental I-O LCA (Chen, 2010), quasi-multi-regional input–output (QMRIO) model (Druckman, 2009), and WRI/WBCSD GHG Protocol (Ozawa-

Meida, 2011). Recently, a truely multi regional IO database has been published and will continuously be updated (CREEA 2014, Tukker et al 2014).

2.1.2 Research trend by region

Considering the publish rate of literature by region, the most of studies on the embodied impacts in building and construction industry have been worked in progress in European and Asian countries. As shown in Figure 2.1and Figure 2.2, Europe and Asia each account for around 43%, and America accounts for only 14%. Among Asian countries, over half of the literature has been published in China. The other leading countries in the field of embodied impacts are the United Kingdom (UK) and USA.



	Published papers
America	23
Europe	72
China	38
Other Asian country	33
International	42
Total	208

Figure 2.1 Published literature by region (Source: Subtask 2 report)

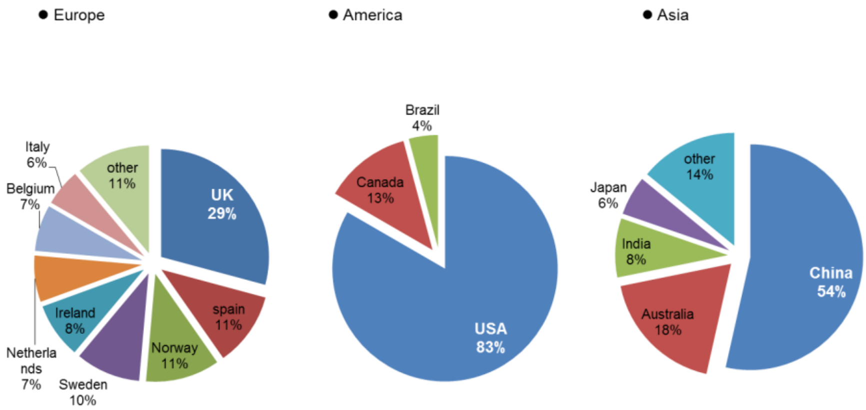


Figure 2.2 Published literature by countries (Source: Subtask 2 report)

2.1.3 EE and EG study Building level

In relation to embodied energy and GHG emissions analysis in the building level, 42 papers have been reviewed. The research subjects at building level are mostly residential buildings, which represent more than 80% of buildings, spread among the following (given in Figure 2.3): low energy building (31%), residential detached housing (27%), multi-story buildings (15%), apartments (11%), offices (8%), and hotels (8%). Papers have a tendency to include only environmental factors in embodied energy and GHG emissions analysis, while several researches consider economic factors together, such as annual running cost (Monahan, 2010) or life cycle cost (Mithraratne *et al.*, 2004). Assessment periods vary from 1 - 100 years. The most preferable assessment period is 50 years (47%) for analyzing embodied impacts from a building's life cycle.

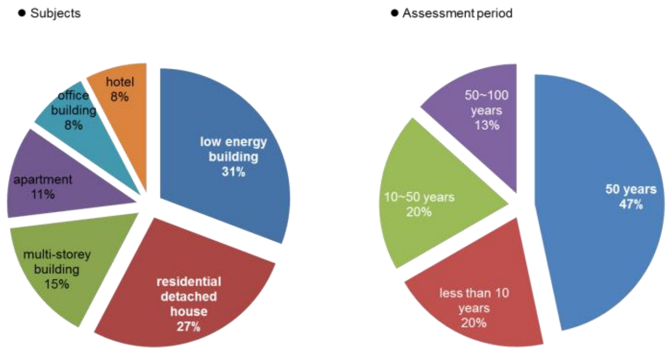


Figure 2.3 Research subjects and assessment period at building level (Source: Subtask 2 report)

(1) Methodology

Both process-based LCA and I-O LCA methodologies are widely applied to evaluation in building levels, shown in Table 2.1(1) and Table 2.1(2).

In order to analyze the relation between research objectives and system boundary settings, environmental factors are classified into four categories: Embodied Energy (EE), Embodied GHG emissions (EG), Operational Energy (OE), and Operational CO_2 (OC). Also, system boundaries are divided into five different stages: Material production (P), Material transportation to site (T), Construction (C), Building operation (O), and End of Life (EOL). EOL (End of life). Literature review results show that there was no direct correlation between environmental factor selection and system boundary set-up (Figure 2.4). Due to absence of clear guideline to evaluate embodied energy and GHG emissions, researchers chose the environmental factors and set system boundaries according to their objectives, so that it is impossible to compare between different case studies.

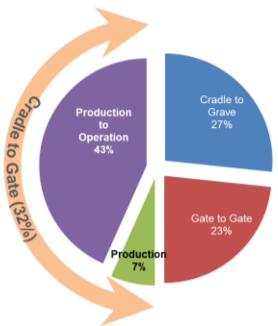


Figure 2.4 System boundary setting at building level (Source: Subtask 2 report)

Half of the cases set up cradle-to-gate life cycles, and most assessments proceeded from the production stage to the building operation stage. The reference flow was measured in m2 or m3. The results of embodied energy were expressed in MJ or kWh units, while that of embodied CO2 was commonly measured in GWP.

Table 2.1 Summary of the reviewed case studies at building level (1) (Source: Subtask 2 report)

No.	Author (year)	Objectives	Building type	Methodology	Period (year)	Environmental factor[1]				unit	
						EE	OE	EC	OC	EE	EC
1	Thormark (2002)	Analysis recycling potential	Residential	Process based LCA	50	√	√			MJ, kwh	
2	Mithraratne (2004)	Comparison light, RC, super-insulated houses	Residential	I-O LCA	100	√				MJ	
3	Karlsson (2007)	Comparison conventional vs. low tech	Residential	Process based LCA	50	√	√			kwh	
4	Hacker (2008)	Analysis	Residential	Process based LCA	100			√	√		GWP
5	Shukla (2009)	Analysis	Residential	Process based LCA	annual	√	√			MJ	
6	Mahdavi (2010)	Comparison Passive vs. Low energy	Residential	Process based LCA	0.5	√	√	√	√	kwh	GWP
7	Monahan (2010)	Comparison Active tech.	Residential	Process based LCA	20	√	√	√	√	kwh	GWP
8	Rossello –Batle (2010)	Analysis	Hotel	Process based LCA	annual	√				MJ	GWP
9	Verbeeck (2010)	Creating building LCI massive vs. light envelope	Residential	Process based LCA I-O LCA	30, 60, 90	√		√		MJ	GWP
10	Verbeeck (2010)	Comparison	Residential	Process based LCA I-O LCA	30, 60, 90	√		√		MJ	GWP
11	Rai (2011)	Analysis	Office	Process based LCA I-O LCA	25			√	√		GWP
12	Dodoo (2011)	Analysis	Residential	Process based LCA I-O LCA	50	√	√			kWh	
13	Ramesh (2012)	Comparison	Residential	Process based LCA I-O LCA	75	√				kWh	
14	Rossi (2012)	Comparison steel frame and masonry	Residential	Process based LCA	annual			√	√		GWP
15	Rossi (2012)	Comparison steel frame and masonry	Residential	Process based LCA	annual			√	√		GWP
16	Ooteghem (2012)	Comparison steel and timber	Residential	Process based LCA	50	√	√	√	√	MJ	GWP

[1] EE = Embodied energy, OE = Operational energy, EG = Embodied GHG, OC = Operational CO_2

Table 2.1 Summary of reviewed case studies at building level (2)
(Source: Subtask 2 report)

No.	Author (year)	System boundary[1]					Reference flow	LCI DB	Tools S/W	Data collection sources		
		P	T	C	O	EOL				field survey	monitoring	Energy simulation
1	Thormark (2002)	√	√		√		m²	Literature		√		DEROB-LTH
2	Mithraratne (2004)	√		√	√		-	Literature	invented model	√		
3	Karlsson (2007)	√			√		m²	Literature			√	
4	Hacker (2008)	√			√		building	Literature		√	√	ENERGY 2
5	Shukla (2009)	√	√	√	√		m²	Calculated		√		
6	Mahdavi (2010)	√			√	√	m²	Literature		√	√	
7	Monahan (2010)	√	√	√	√		m²	National LCI DB, DECC, Beggs	SimaPRO	√	√	UK SAP methodology
8	Rossello –Batle (2010)	√	√	√	√	√	m²	BEDEC PR/PCT Literature	TCQ2000			
9	Verbeeck (2010)	√	√		√		m³	Ecoinvent		√		TRNSYS
10	Verbeeck (2010)	√	√		√		m³	Ecoinvent		√		TRNSYS
11	Rai (2011)	√			√		-	National LCI DB, Bath ICE	SimaPRO			Ecotect
12	Dodoo (2011)	√	√	√	√	√	m²	Calculated		√		ENORM ENSYST
13	Ramesh (2012)	√			√		m²	Literature		√		Design builder
14	Rossi (2012)	√			√		-	BEEs, CRTI, Ecoinvent	Equer	√		Pleiades + Comfie
15	Rossi (2012)	√			√		-	BEEs, CRTI, Ecoinvent	Equer	√		Pleiades + Comfie
16	Ooteghem (2012)	√	√	√	√	√	m²	National LCI DB	ATHENA	√		eQUEST

[1] P = Production, T = Transportation to site, C = Construction, O = Operation, EOL = End of life

(2) Calculation and Database

For assessing embodied energy and GHG emission in building life cycle perspectives, energy (36%) only or energy and material together (36%) were selected as the calculation parameters, as shown in Figure 2.5. Most researchers obtained data for calculation from field surveys, monitoring (32%), and national statistics database (18%), such as BEDEC, PR/PCT, or DECC. Owing to a lack of developed national average databases, however, the papers published before year 2010 have shown a tendency to collect LCI databases on embodied energy/CO_2 from unspecified literature and to invent an evaluation tool for the researcher's own purpose. After it became easier to access to national LCI databases, more researchers have used domestic LCI databases that reflect the situation of domestic industry and life habit factors. Besides the national LCI DB, ecoinvent, KBOB, Bath ICE, and BEES were also preferable databases to obtain embodied energy consumption and equivalent CO_2 emissions. SimaPRO, TCQ2000, ATHENA, and Equer software were used as LCA calculation tools. Interestingly, almost all research cases have gathered operational data from both field survey methods and energy simulation tools, such as TRNSYS, Ecotect, ENORM ENSYST, Energy Plus (e+), Design builder, or eQUEST, rather than energy monitoring, which was common before year 2010.

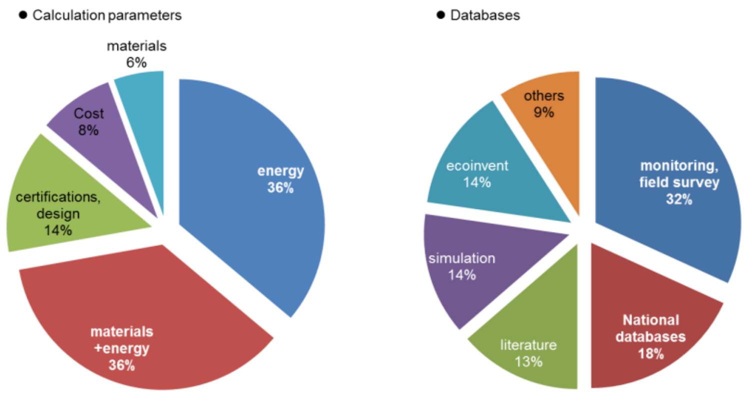


Figure 2.5 Calculation parameters and sources of LCI DB at building level (Source: Subtask 2 report)

2.1.4 EE and EG study for Building component level

21 papers have been reviewed in relation to embodied energy and GHG emissions analysis at building component level (Figure 2.6). The research subjects at building component level vary: structure (25%), various building elements (25%), building envelopes (13%), building equipment (13%), wall systems (12%), openings (6%), and roof systems (6%). Most papers included only environmental factors in embodied energy/ CO_2 analysis, while only one paper considered economic and social factors in comparison of wood and steel window frames (Abeysundra, 2007).

On the whole, most literature analyzed the embodied energy as environmental factors. The embodied CO_2 was considered as a secondary parameter to compare the environmental impacts from different materials by components. Assessment periods varied from 0 to 60 years. More than half of the researchers did not set the assessment period to analyze embodied impacts from building components. Only a few papers showed the results during a 40-60 year lifespan.

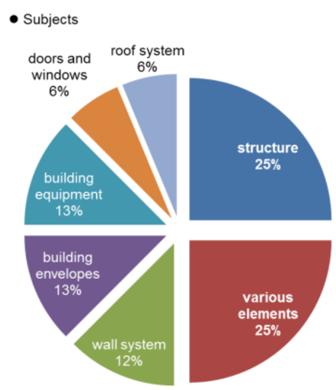


Figure 2.6 Research subjects at building component level (Source: Subtask 2 report)

(1) Methodology

The reviewed papers used process based LCA, I-O LCA, Hybrid LCA and LCEA method. The most dominant methodologies are process based LCA and I-O based LCA at building component level. Unlike the embodied energy and GHG emissions at building level, I-O based LCA was applied to cases with a 0-year lifespan. The result of this review of the methodologies at building component level, however, does not support that one methodology is superior to all others, according to the system's boundary and lifespan setting.

Approximately 60% of the cases set up a cradle-to-gate life cycle that includes the production-to-operation stage (33%) and the production stage (27%). The reference flow was measured in weight, volume and area unit. The results of the embodied energy were expressed in MJ units, while those of the embodied CO_2 were commonly measured in GWP, particularly in one case that presented the results for CO_2 and SO_2.

(2) Calculation and Databases

The calculation parameters were energy and materials together (47%), or energy (16%) only for assessing the embodied energy and GHG emissions in building the components' lifespan, as shown in Figure 2.5. Most researchers obtained data from field surveys and monitoring (37%), literature (26%), simulations (11%), National statistics database (10%), ecoinvent (5%), and other sources (11%). In comparison with energy data sources in the building level, the energy simulation tools used in the case study were relatively poorer in analyzing the embodied energy and GHG emissions of the building components.

2.2 Current state of practical application

The aspects of EE and EG as part of a full LCA have started attracting more and more interest from different actors in the building and construction supply chain. This happens in different ways. For example, some local authorities have already included mandatory embodied carbon assessment as part of the planning process (Brighton and Hove City Council, 2011), designers and engineers have started looking into embodied impacts as part of LCA to develop design options (AIA, 2010), quantity surveyors are now invited to calculate embodied carbon and add this dimension to their reports (RICS, 2012), construction product manufacturers both in EU and internationally are increasingly requested to develop and communicate credible and transparent LCA data to purchasers in the form of Environmental Product Declarations EPDs (ISO 14025:2006, EN 15804:2012), or even more specifically to communicate the carbon footprint of products (ISO/TS 14067:2013). At the same time, progressive clients and developers in their attempt of adopting leading sustainability practices have started looking at ways for considering and reducing the embodied impacts of their developments (UK GBC, 2015).

The practical application of these new aspects is partially facilitated by a new stream of various publications in the form of guidelines specific to different building-industry stakeholder groups dealing with LCA as a whole, or specifically with the aspects of embodied energy and embodied carbon, reflecting the increasing interest in the consideration of embodied impacts in their everyday work. Table 2.2 presents examples of EE and EG related guidelines published by different associations and organizations to be used by their members.

Table 2.2 List of existing guidelines published by various associations and organisations (Source: Subtask 1 report)

Title of document	Year	Main target group (Secondary target group)	Scope of application and limitations
RICS - Methodology for the calculation of embodied GHG as part of the life cycle carbon emissions for a building	2012	Quantity Surveyors (Decisions makers in the design team)	Europe (particularly UK) *Information paper*
UK CPA (Construction Products Association) - Guide to understanding the embodied impacts of construction products	2012	Construction Product Manufacturers (Design professionals and consultants)	Europe (particularly UK) *Information paper*
BSRIA (Building Services Research & Information Association)- Inventory of Carbon & Energy (ICE) summary guide	2011	Building services engineers	Europe (particularly UK) *Guide*
ENCORD (European Network of Construction Companies for Research and Development) – Construction CO2e Measurement Protocol - A Guide to reporting against the Green House Gas Protocol for Construction Companies	2012	Construction Companies acting as a main contractor or a large subcontractor (construction companies who manufacture materials or construction companies who operate buildings)	Europe *Measurement Protocol*
AIA (The American Institute of Architects) – AIA Guide to Building Life Cycle Assessment in Practice	2010	Architects	United States *Guide*
WRAP (Waste & Resources Action Programme) – Guidance for low carbon building projects and estates management	2011	Construction clients, Property owners, Building managers **(**Design teams, contractors and facilities managers when appointing their supply chains)	UK *Guidance for low carbon building projects and estates management*
European Commission – EeBGuide Guidance Document - Operational Guidance for Life Cycle Assessment Studies of the Energy-Efficient Building Initiative	2012	LCA practitioners, LCA tool developers (Experts responsible for the definition of calculation rules for building labelling systems and for EPD programmes)	Europe *Guidance document*
UK GBC – Tackling Embodied Carbon in Buildings	2015	Clients and Developers	UK *Guide for the client sector*
ICE (Institution of Civil Engineers) – Energy Briefing Sheet: Embodied Energy and Carbon	2015	Civil engineers	UK (also operates around the world) *Briefing sheet*
KBOB – Guidelines for life cycle assessments of construction products and for buildings	2012-2016	Civil engineers, architects, manufacturers	Switzerland *Guidance document*

2.3 Issues in EE and EG

The methods of calculating embodied energy and embodied GHG emissions in the building and construction sector are unclear, if not confusing, to many, and the interpretation of the results do not usually match the calculation method or its appropriate application. Some of the noted challenges include:

- Inaccuracy and incompleteness of the quantification approach
- Different quantification methodology
- Different system boundary definition
- Data quality

The availability and accessibility of data and information on embodied energy and embodied GHG emissions of building materials and products constituting the building is the most important requirement for the assessment of embodied energy and embodied GHG emissions of a building. However, this information should be reliable so as to allow for useful comparisons to be drawn between building products, or between building materials.

At present, not all construction product data are collected using consistent boundaries of assessment, and product specific data from manufacturers are not always comparable with the more generic product data.

System boundary settings, modelling approaches (e.g. allocation) and background data may vary and by that exerting a substantial influence on the resulting environmental impacts.

Depending on different boundary conditions, data sources and methodology, results may vary (sometimes very significantly), and thus influence key decisions by stakeholders. For designers and consultants, for example, Lützkendorf et al (2014) have presented practical guidance (e.g., system boundary, clear definitions, data source documentation, etc) on incorporating embodied impacts in the building design and procurement process.

Many have previously argued the need to develop clear guidelines on the methods of calculation and applications of the embodied energy and embodied GHG emissions for different stakeholders in the building and construction sector (Balouktsi et al., 2015; Lützkendorf et al., 2014; Dixit et al., 2013, 2015; UKGBC, 2014).

Summary of Current Needs

The current development of life cycle approaches and design methods to improve the overall sustainability of buildings makes necessary the explicit incorporation of the aspects of embodied energy and embodied GHG emissions into the assessment of the environmental performance of buildings as part of a complete sustainability assessment. However, limited attention has been paid so far to the embodied impacts compared to the focused efforts of building and construction industry on reducing the operational part of life cycle energy of buildings. The influence of these aspects becomes even more critical for energy-efficient, low-energy or net-zero energy building concepts, since these are usually linked with the integration of energy and carbon-intensive materials and products. However, as Langston (2008) suggests, while measuring operating energy is easy and less complicated, determining embodied energy is more complex and time consuming.

Investigating the current situation and conditions, the assessment of EE and EC at the building level is now possible, as

- the scientific knowledge and basis exists since decades
- the currently available life cycle oriented international and European standards form the basis for a quantitative assessment of EE and EG among other parameters,
- the increasing integration of LCA approaches into widely known sustainability assessment and certification systems for buildings facilitates the spread of life cycle thinking in the building industry,
- the current availability and access to LCA data, EPD's and tools worldwide is sufficient to support an assessment of EE and EG, even from the early design stages of building projects,

Nevertheless, these standards, data and tools, do not always define clearly the system boundaries, indicators, etc. leaving a broad scope for interpretation and creating uncertainty. There is still a lot of confusion partly owning to the fact that there are no clear and commonly accepted definitions and system boundaries. The spectrum of definitions ranges from accounting only for initial EE and EG of construction products (production stage) to accounting for the whole life cycle (production, construction, maintenance and end of life of the building) plus sometimes even the end of life recycling and recovery benefits. It is a fact that not one size fits all and usually system boundaries are defined subjectively in each study to fit specific purposes. To address areas of confusion, Dixit et al. (2012) brought forward the need for an embodied energy measurement protocol for buildings.

There is a need for

- Clear indicators with proper terms and system boundaries
- A basis for the determination and assessment of embodied GHG emissions at the building level
- A basis for securing transparency in the provision and use of EEG data
- A basis for the determination of data and for the setting up and classification of databases
- Recommendations for the design process to achieve buildings with low embodied impacts
- Recommendations for individual groups of actors playing an important role in the process of minimizing embodied impacts

3. Definition of EE and EG

3.1 Concepts and considerations for the indicators dealing with EE and EG

3.1.1 Embodied energy

The amount of embodied energy (EE) in the life cycle of a building has become an important criterion in the environmental performance assessment. Appropriate indicators are needed for its quantification and assessment. These should be easy to understand, transparent and easy to interpret, but also these must be able to be determined within a reasonable amount of time and cost. Here, it is a matter of question whether a single indicator is sufficient for expressing the use of resources (in this case of energy) or the use of more indicators or an indicator system is needed.

The development of indicators for the quantification and assessment of EE is closely linked to the respective definition. It can be said that the energy consumed in life cycle stages of a building other than the operation (space conditioning, water heating, lighting, operating building appliances and other similar operational activities) is the so-called "embodied energy" of the building (Dixit et al., 2013). These life cycle stages can be the production of building materials and components (raw material extraction, transport, and manufacture), the onsite construction (assembly and installation), the post construction stages such as renovation and refurbishment and the final stages of the building's life cycle such as disassembly, demolition and disposal.

However, defining the term "embodied energy" is not so simple. Sometimes "embodied energy" is referred to in literature as "embedded energy" (European Commission) or "grey energy" (SIA 2032, 2010) among others. Different authors give different interpretations and definitions, representing differences of opinion about the system boundaries (can vary from "cradle to gate" to "cradle to grave") to be adopted and type of energy (primary or delivered? Which forms of primary energy are considered and how they are aggregated? Is feedstock energy considered?) to be included in embodied energy evaluation(see e.g. Frischknecht et al. 2015). The main parameters that are usually open to misinterpretations and unclearly defined across studies in relation to EE were discussed and presented in detail in ST1 report.

Some conclusions from this analysis were:

- At the moment, in most of the cases the key indicator for assessing "embodied energy" is the non-renewable primary energy consumption. However, some assessment systems and standards consider also the renewable part of energy either separately or in an indicator expressing the total primary embodied energy.
- Feedstock energy (both renewable and non-renewable) is an important parameter in an embodied energy analysis. Usually, it is reported separately from the overall embodied energy result.

- The type of the selected approach for aggregating the different forms of primary energy resources has a great influence on the Cumulative Energy Demand (CED) result – however, for EE these differences are proved to be less significant than for the operation phase (Frischknecht et al. 2015)..

3.1.2 Embodied GHG emissions

The preservation of the Earth's ecosystem (being the natural foundation of life) is a central task in the design of buildings. Thus, it is necessary to determine, assess and influence in a targeted manner the effects on the global environment. It is useful to consider this as a criterion of environmental performance and to develop appropriate indicators for its quantification. In the past these effects were mainly assessed indirectly through the assessment of energy consumption, but nowadays it has become increasingly important – even in connection with the results from COP 21 in Paris – to measure in a direct way the contribution of buildings to the greenhouse effect. Currently, there are many ongoing initiatives around the subject of carbon footprint. Specific recommendations about the use of appropriate indicators for the quantification of embodied GHG emissions derived from this discussion are given here.

Embodied GHG emissions represent first of all the GHG emissions associated with the energy consumption for the production, construction, maintenance, repair, replacement, refurbishment and EOL of the building (embodied energy consumption) and in addition also sometimes, the GHG emissions arising as a result of specific chemical processes as part of the manufacturing process of specific construction products and/or during the use of such products. However, defining embodied GHG emissions is not so simple. Different authors give different interpretations and definitions, representing differences of opinion about the system boundaries to be adopted and type of emissions to be included in the evaluation. In the past, "embodied CO_{2eq}" was often referred to in literature as "embodied carbon" (RICS, 2012; Anderson and Thornback, 2012), or "grey GHG emissions" (SIA 2032, 2010) among others.

In order to avoid misunderstandings and confusion with biogenic carbon one should not speak of embodied carbon but of embodied GHG emissions.

Specifically, the discussion focused on these issues:

- types of GHG emissions included in the calculation
- the characterization factors for the conversion of greenhouse gases in CO_{2eq}
- the different sources of GHG emissions
- carbon sequestration or storage in materials

Some conclusions from this analysis were:

Currently, in the application and interpretation of the different indicators ambiguities and uncertainties still exist with regard to the type and scope of the greenhouse gases considered, whether or not the process-related emissions are taken into account, or how to deal with the F-gases emitted from the insulation and cooling systems during the use stage among others. In this sense, an urgent need for clear definitions, system boundaries and possibilities of interpretation exists.

Dealing with stored carbon in bio-based products is an important issue. Solutions must be developed to address it appropriately. However, it is clear that a separate consideration of this effect from the overall assessment results is necessary.

3.2 Definition of EE and EG

3.2.1 Definition of embodied energy and embodied GHG emissions

Embodied energy (EE) is the energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery (YourHome, 2013; Sartori and Hestnes, 2006; Hammond and Jones, 2008).

In the building case, embodied energy comprises of the energy consumption from the use of construction materials, products and processes during its construction, maintenance and demolition (Dixit et al., 2010; Treloar, 1998; Angelini and Nawar 2008).

Embodied CO_2 emission is the total carbon dioxide equivalent (CO_{2eq}) gases that are emitted from the formation of buildings, their refurbishment, and subsequent maintenance (UKWIR, 2008; RICS 2011).

Annex57 report describes the definition of EE and EG as an example and users may chose the definition of EE and EG based on their own decision.

(1) Primary energy at calculating EE

Primary energy at calculating EE is defined as follows (see also Frischknecht et al. 2015);

Non-renewable energies

(a) Fossil fuels

It is generally used heating values of fossil energy resources, thus including energy consumption associated with extraction, transportation and refinement processes.

(b) Nuclear fuel

Energy value of Uranium extracted from the ground, thus including energy consumption associated with extraction, conversion, enrichment, fabrication and final disposal of the fuel as well as erection and dismantling of the nuclear power plant

Renewable energies

(c) Hydropower

The potential energy in the dam quantifies the primary energy required to produce electricity

(d) Solar energy

The solar energy harvested to produce electricity.

(e) Wind energy

The kinetic energy harvested to produce electricity.

(f) Biomass energy

The energy content of the biomass harvested.

According to the AnnexII Methodology in the IPCC report (Reference 38), methods how to calculate primary energy accounting as follows;

- Hydropower and solar PV: 100% conversion efficiency to 'primary electricity', the gross energy input for the source is 3.6 MJ of primary energy = 1 kWh electricity.
- Nuclear energy: 33% thermal conversion efficiency, 1 kWh electricity = (3.6 ÷ 0.33) = 10.9 MJ Nuclear energy.
- Geothermal energy: 10% conversion efficiency for geothermal electricity, 1 kWh = (3.6 ÷ 0.1) = 36 MJ), and 50% for geothermal heat, if no country specific information is available.

This method is used in IEA statistics but not used in life cycle assessments and calculations of embodied energy and carbon.

Following definitions are proposed, based on the treatment of renewable energy source(s).

EE1

Embodied energy 1 (EE1) is the cumulative non-renewable primary energy demand (CEDnr) except for nuclear energy, for all processes related to the creation of a product, its maintenance and end-of-life.

EE2

Embodied energy 2 (EE2) is the cumulative non-renewable primary energy demand (CEDnr) for all processes related to the creation of a product, its maintenance and end-of-life.

EE3

Embodied energy 3 (EE3) is the cumulative primary energy (renewable and non-renewable) demand (CEDnr+r) for all processes related to the creation of a product, its maintenance and end-of-life.

Embodied energy consumption in both approaches includes the energy consumption for the initial stages, the recurrent processes and the end of life processes of the product. The unit for both definitions is "MJ/reference unit/year of reference study period (RSP)".

(2) CO_{2eq} at calculating EG

Embodied GHG associated buildings are shown as follows;

(a) Fuel-related GHG emissions

(a1) as energy source

(a2) as feedstock

(b) Process-related GHG emissions

(c) Fluorocarbon

(d) Stored carbon

3.2.2 *EE and EG in life cycle*

(1) Life cycle model

A building's life cycle includes mainly four phases: "Product" (creation or manufacture), "Construction", "Use" and "End of life" as shown in Figure 3.1. Over the life cycle of building, each phase contributes either directly or indirectly to embodied energy and embodied GHG emissions impacts. In a building's life cycle, for example, the embodied energy or embodied GHG emissions in the "Product" stage includes those in the extraction of raw materials, including transport, and in product manufacturing (Figure 3.1). In the "Construction" phase, energy is consumed directly on the site due to use of machinery. This is classified as direct embodied impacts of the building. In the use stage, all the sub-categories (B1 to B5) as shown in Figure 3.1 are included over the building's life cycle. Due to its repetition during the building's service life, this is sometimes called "recurring embodied impact". Not shown in Figure 3.1 is the energy consumed during building operation, labelled B6 (Operational energy use); this is not counted in embodied impacts calculation. Finally, the energy consumed to deconstruct, transport, process and/or dispose waste is included in the indirect embodied impacts in the "End of life" stage.

	BUILDING LIFE CYCLE																ADDITIONAL INFORMATION
	PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				POTENTIAL BENEFITS & LOADS
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use, installed products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction	Transport	Waste processing	Disposal	Recovery – Reuse – Recycling - potential
Embodied	✓	✓	✓	✓	✓	✓*	✓	✓	✓	✓			✓	✓	✓	✓	(✓)
Operational											✓	✓					(✓)

* is relevant for materials or products emitting or binding GHGs in the use stage

Figure 3.1 Building life cycle stages according to EN 15978:2011. The life cycle stages related to embodied impacts are indicated separately than the ones related operation impacts. (Source: Subtask 1 report)

(2) System boundary variations

The embodied energy (EE) and embodied GHG emissions (EG) associated with a building can be categorised into various system boundaries based on the parts of the full life cycle included in the assessment. Interestingly, there are some boundary variations commonly used in the industry. Based on these variations, Annex 57 has created a model/typology of different system boundary selection possibilities to fit the varying needs of each actor. In order to describe and declare the different system boundaries in a consistent and widely accepted way, the modular life cycle model from EN 15978:2011 (it is based on the modular setup first developed by international ISO/ TC 59/ SC 17 group in ISO 21931-1:2010) was adopted.

The proposed model is illustrated in Figure 3.2 and includes the following types:

System Boundary type I: Cradle to Gate

This boundary includes only the production stage of the construction products integrated into the building. Processes taken into account are: the extraction of raw materials, transport of these materials to the manufacturing site and the manufacturing process of the construction products itself. Thus, in the case of a building the impacts of this stage are accounted for as the sum total of the "cradle to gate" impacts of its individual components.

System boundary type II: Cradle to Site

Cradle to gate boundary plus delivery to the construction site.

System boundary type III: Cradle to Handover

Cradle to site boundary plus the processes of construction and assembly on site.

System boundary type IV: Cradle to End-of-Use

Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy and emissions. This boundary marks the end of first use of the building.

System boundary type V: Cradle to Grave

The cradle to grave system boundary includes the "cradle to end of use" boundary plus the end of life stage with processes such as building deconstruction or demolition, waste treatment and disposal (grave).

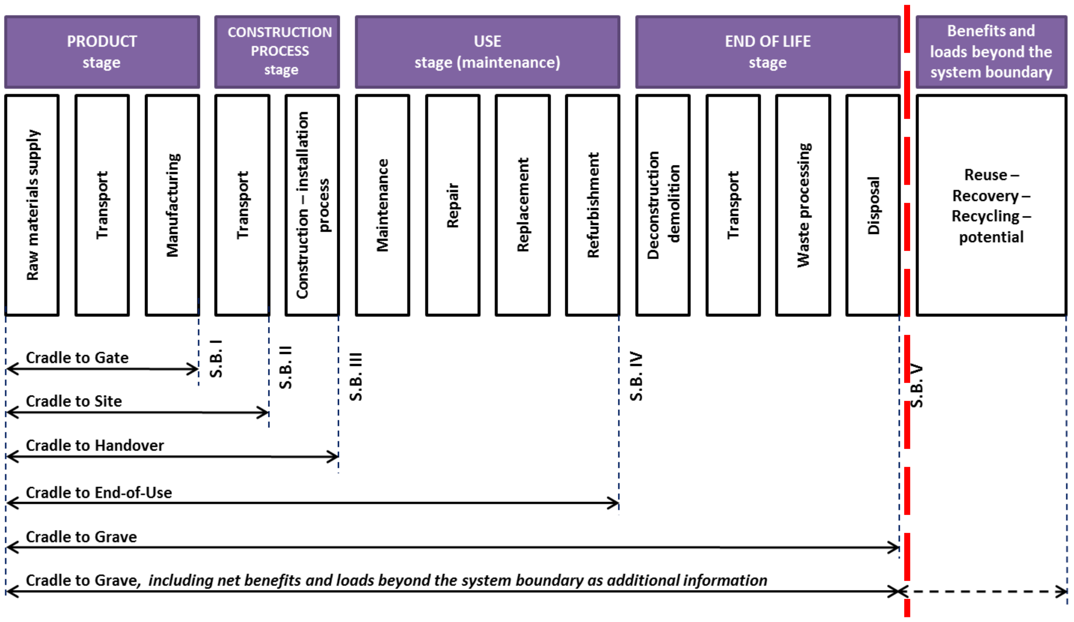


Figure 3.2 Proposed model for system boundary description and selection (Source: Subtask 1 report)

It is advisable where possible embodied impacts from all life cycle stages to be considered (*type V*), as it represents the comprehensive embodied impacts caused by the entire life cycle of the building under analysis. If this is not possible due to lack of appropriate data, the system boundary *Cradle to Handover (type III)* should be used at the minimum, as it represents the initial embodied impacts of the whole building. In addition to the respective results, also the partial results for each included module should be declared. When considering the system boundary type VI, the result of system boundary type III has also to be shown separately (initial EE and EG).

The *net benefits and impacts beyond the system boundary* (e.g. possible savings accruing to a second user from the use of recycled steel) may be quantified and if so they shall be reported separately as additional information. This is covered by module D as referred to in ISO 21929-1:2011 and further defined in EN 15978:2011. Under certain conditions and circumstances, such an information module (D) can be characterized as recycling potential of the building. This requires, among others, the declaration of an appropriate scenario for deconstruction and selective dismantling (to recover the materials to be recycled) in module C1 on building level.

The commonalities and differences between embodied energy and embodied CO_2 emissions in terms of life cycle boundary and source of contributions are given as shown in Table 3.1.

Table 3.1 Boundary and emission sources for the embodied energy and embodied GHG emissions of building/building products

	Life cycle boundary			Source
Embodied energy	Initial	Material	Cradle to gate	Energy requirements to; • Extraction of raw material • Processing material • Assembly of product/components • Transport between companies for each step
		Construction	Site	Energy requirements to; • Transport to site • Site activities • Disposal of waste
	Recurring		Refurbishment and maintenance	Energy requirements to; • Replace material/components • Transport between gate to building • Repair • Transport of material/components to disposal
	Demolition		End-of-life	Energy requirements to; • Deconstruction • Disposal including transport
Embodied GHG emissions (or, embodied carbon)	Initial	Material	Cradle to gate	CO_2 emissions (CO_{2eq}) due to; • Energy consumption of initial embodied energy above • Chemical reaction (e.g., clinker production of cement) • Sequestration of carbon absorbed (e.g., timber) [1])
		Construction	Site	CO_2 emissions (CO_{2eq}) due to; • Energy consumption of construction energy
	Recurring		Refurbishment & maintenance	CO_2 emissions (CO_{2eq}) due to; • Recurring embodied energy above • Chemical reaction (e.g., clinker production of cement) • Sequestration of carbon absorbed (e.g., timber)
	Demolition		End-of-life	CO_2 emissions (CO_{2eq}) due to; • Energy consumption of demolition energy above • burning fossil-based materials • burning renewable materials (e.g. timber) [2])

[1]): only if biogenic carbon dioxide emitted is assessed with a GWP = 1 kg CO_2-eq/kg biogenic CO_2

[2]): only if carbon sequestration is assessed with a GWP = - 3.67 kg CO_2-eq/kg biogenic Carbon

3.3 Reporting and documentation of EE and EG

Specific recommendations were developed within the scope of IEA-EBC Annex 57 aiming at providing, on the one hand, more transparency in reporting and documentation of different parameters and on the one hand, at promoting harmonization among studies.

3.3.1 Object of Assessment

The recommendations provided focus on improving the completeness of the description of the building and increasing the transparency level of this process. This is achieved by providing different checklists, which serve two purposes: one the one hand, to show the recommended approach of Annex 57 by highlighting specific items that need to be considered in the analysis, and on the other hand, to allow different stakeholders to define and report their case studies transparently, in case they choose to follow another approach than the one recommended here.

3.3.2 Description of the Building

The spatial boundary specifying the part of the physical building that is included in an assessment may range from single building components to neighbourhoods. That’s why this needs always to be clearly defined and reported. In the context of IEA EBC Annex 57 the object of assessment is only the building.

However, in early design stages simplifications and omissions should be allowed. High-impact building components that contribute to the biggest part of the overall embodied energy and embodied GHG emissions should be focused in the early design stage. In any case, it is advisable to include in an EE and EG assessment, if possible, the building elements crossed in Table 3.2 as a checklist for declaring transparently the scope of the building analysis, and in this way allowing comparisons between studies.

Table 3.2 List of building elements that should be included in the EEG analysis (Source: Subtask 1 report)

Building Parts	Building Components	Recommended Approach	Own Approach
Substructure	Foundations	X	
	Basement retaining walls	X	
	Ground floor construction	X	
Superstructure	Frame	X	
	External walls	X	
	External doors	X	
	Windows	X	
	Internal walls	X	
	Floors	X	
	Ceilings	X	
	Roof	X	
	Stairs and ramps	X	
Building services	Water system	X	
	Sewage system	X	
	Heating system	X	
	Cooling system	X	
	Ventilation system	X	
	Electrical system	X	
	Conveying systems	X	
	Data system		
	Fire protection system		
Finishes	External finishes	X	
	Internal finishes	X	
	Fixed furniture		
	Furniture		
External	Balcony	X	
	Vegetation		
	Pavement		

*The vacant column should be filled out, in case the approach followed is different than the one proposed by Annex 57.

3.3.3 Recommendations for the use of different indicators

For the case of energy it is recommended the indicator to be the Embodied Energy (EE1, EE2 and EE3). The description of the recommended system boundaries for this indicator is shown in Table 3.3 and Table 3.4, which is a checklist for describing in a transparent way the indicator intended to be used in the respective analysis.

For the case of "embodied GHG emissions" the proposed indicator to be used is the Global Warming Potential (GWP 100), according to the most recent IPCC report and as described in Table 3.5. again, a checklist is provided in Table 3.6 for reporting the approach intended to be followed by an individual study in relation to embodied GHG emissions, when this differ from the approach recommended by Annex 57.

Table 3.3 Recommendation of Annex 57 for the indicator Embodied energy (EE1/EE2/EE3) (Source: Subtask 1 report)

EMBODIED ENERGY														
Name of indicator inside Annex 57	Embodied energy (EE1, EE2, EE3)													
Also known as	Embodied energy (EE), Embedded energy, Grey energy, Cumulative energy demand (CED)													
Name in LCIA	EE1 Abiotic Resource Depletion for Fossil Fuels or EE2 Use of non-renewable primary energy or EE3 Use of non-renewable and renewable primary energy													
	EE1 Non-renewable primary energy consumption (fossil) or EE2 Non-renewable primary energy consumption (fossil + nuclear) or EE3 Primary energy total (renewable + non-renewable)													
Target	EE1 Protection of fossil energy resources EE2 Protection of non-renewable energy resources EE3 Reduction of primary energy demand, Protection of non-renewable and renewable energy resources													
Definition	EE1, EE2, EE3 see definition of EE													
System boundaries	System boundary type V - "Cradle to Grave" Feedstock energy (non-renewable) is included and may be reported separately. If calculated, benefits and loads beyond the life cycle of the building shall be reported separately – Module D													
Included Modules	**A1**	**A2**	**A3**	**A4**	**A5**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**D**
	Raw Material Supply	**Transport to Manufacturer**	**Manufacturing**	**Transport to Building Site**	**Installation into Building**	**Maintenance**	**Repair**	**Replacement**	**Refurbishment**	**Deconstruction/ Demolition**	**Transport to EOL**	**Waste Processing**	**Disposal**	**Reuse, recycling or recovery potential**
	X	**(X)[1]**	**X**	**(X)**	**(X)**	**(X)**	**(X)**	**X**	**(X)**	**X**	**(X)**	**X**	**X**	**(X)**
Unit	MJ/reference unit/year (of the RSP)													

Sub-information:
The results of embodied GHG emissions should be presented in both an aggregated and disaggregated form for each module.
For the aggregated results, apart from system boundary type V - "Cradle to Grave", also the system boundary *"Cradle to Handover"* should be used as sub-setting at the minimum, as it represents the initial emissions of the whole building.
Following the idea of modularity of CEN TC 350 standards, at the highest level of disaggregation the results of the indicator should be expressed in 'information modules' recording the impact occurred in each module of each life cycle stage.

[1] The brackets mean that these activities are included only when there is data available.

Table 3.4 Checklist for declaring the scope of the indicator EE1, EE2 or EE3 (Source: Subtask 1 report)

		Recommended Approach			Individual approach
Included non –renewable energy resources		**EE1**	**EE2**	**EE3**	
Fossil fuels as energy		X	(X)	(X)	
Fossil fuels as feedstock		X	(X)	(X)	
Nuclear fuels			X	X	
Included renewable energy resources					
Biomass total				X	
Biomass as feedstock				(X)	
Solar energy				X	
Hydropower				X	
Wind power				X	
Geothermal energy				X	
Type of System Boundary					
Cradle to Gate					
Cradle to Site					
Cradle to Handover					
Cradle to End of Use					
Cradle to Grave		X	X	X	
Cradle to Grave + Module D					
Unit of Measurement					
MJ/reference unit/year of the RSP (e.g. 50 years)		X	X	X	
MJ/reference unit/year of the RSL					
MJ/reference unit (absolute)					
kWh/reference unit/year of the RSP(e.g.50 years)					
kWh/reference unit/year of the RSL					
kWh/reference unit (absolute)					
If other, please declare					
Reference Unit					
Gross Floor Area (GFA)		X	X	X	
Net Floor Area (NFA)					
If other, please declare					
Included Processes in Detail / Modules					
A1	Raw Material Supply	X	X	X	
A2	Transport to Manufacturer	X	X	X	
A3	Manufacturing	X	X	X	
A4	Transport to building site	(X)[2]	(X)	(X)	
A5	Installation into building	(X)	(X)	(X)	
B2	Maintenance	(X)	(X)	(X)	
B3	Repair	(X)	(X)	(X)	
B4	Replacement	X	X	X	
B5	Refurbishment	(X)	(X)	(X)	
C1	Deconstruction/ Demolition	X	X	X	
C2	Transport to EOL	(X)	(X)	(X)	
C3	Waste processing	X	X	X	
C4	Disposal	X	X	X	
D	Reuse, recovery or recycling potential	(X)	(X)	(X)	

[2] The brackets mean that these activities are included only when there is data available or if considered appropriate.

Table 3.5 Recommendation of Annex 57 for the indicator Embodied GHG Emissions (Source: Subtask 1 report)

Embodied GHG Emissions	
Name of indicator inside Annex 57	Embodied GHG emissions (EG1 and EG2)
Also known as	Embodied CO_2 emissions, Embodied carbon, Partial Carbon Footprint, Embedded Carbon, ECO_2.
Name in LCIA	Global Warming Potential, GWP for the creation, maintenance and end-of-life of the building
Metric	EG1 Global Warming Potential (GWP100) (including the GHGs as presented in the 5th IPCC report) EG2 Global Warming Potential (GWP100) (including only CO_2 and F-gasses)
Target	Prevent or reduce climate change
Definition	Embodied GHG emissions is the cumulative quantity of greenhouse gases, which are emitted during all of the processes related to the creation of the product[3], its maintenance and end-of-life. This is calculated and expressed as CO_2 equivalent.”
System Boundaries	System boundary type V - “Cradle to Grave” Non-fuel related emissions are also included (e.g. due to chemical effects) If calculated, benefits and loads beyond the life cycle of the building shall be reported separately – Module D Carbon sequestration should be reported separately.
Included Modules	(see below)
Unit	$kgCO_{2eq.}$/reference unit/year (of the RSP)

Included Modules

A1	A2	A	A4	A5	B2	B3	B4	B5	C1	C2	C3	C	D
Raw Material Supply	**Transport to Manufacturer**	**Manufacturing**	**Transport to Building Site**	**Installation into Building**	**Maintenance**	**Repair**	**Replacement**	**Refurbishment**	**Deconstruction/ Demolition**	**Transport to EOL**	**Waste Processing**	**Disposal**	**Reuse, recycling or recovery potential**
X	X	X	(X)[4]	(X)	(X)	(X)	X	(X)	X	(X)	X	X	(X)

Sub-information:

The results of embodied GHG emissions should be presented in both an aggregated and disaggregated form for each module.
For the aggregated results, apart from system boundary type V - “Cradle to Grave”, also the system boundary *“Cradle to Handover”* should be used as sub-setting at the minimum, as it represents the initial emissions of the whole building.
Following the idea of modularity of CEN TC 350 standards, at the highest level of disaggregation the results of the indicator should be expressed in ‘information modules’ recording the impact occurred in each module of each life cycle stage.

[3] In our case products are construction products, constructed assets and buildings.
[4] The brackets mean that these activities are included only when there is data available.

Table 3.6 Checklist for declaring the scope of the indicator embodied GHG emissions used for each individual study, in case the approach followed is different from the one recommended by Annex 57. (Source: Subtask 1 report)

Checklist for defining the character of the indicator(s) used for EG:				
Type of GHG emissions		**CO_2+F-gases**	**GWP100**	**Individual approach**
Fuel related		X	X	
Non-fuel related – process related emissions		X	X	
Non-fuel related – Fluorocarbon due to insulation		X	(X)	
Type of System Boundary				
Cradle to Gate				
Cradle to Site				
Cradle to Handover				
Cradle to End of Use				
Cradle to Grave		X	X	
Module D (only as information)			(X)	
Cradle to Cradle				
Unit of Measurement				
$kgCO_{2eq}$ /reference unit/year of RSP (e.g. 50 years)		X	X	
$kgCO_{2eq}$ /reference unit/year of the RSL				
$kgCO_{2eq}$ /reference unit (absolute)				
$kgCO_2$ /reference unit/year of RSP (e.g. 50 years)				
$kgCO_2$ /reference unit/year of the RSL				
$kgCO_2$ /reference unit (absolute)				
If other, please declare				
Included GHG emissions in CO_{2eq}.				
Only CO_2			X	
GHGs as identified in Kyoto Protocol		X	(X)	
GHGs as identified in the 3rd IPCC report				
GHGs as identified in the 4th IPCC report, Chapter 8				
GHGs as identified in the 5th IPCC report				
Fluorocarbon as defined in Montreal protocol				
If other, please declare				
Reference Unit				
Gross Floor Area (GFA)		X	X	
Net Floor Area (NFA)				
Energy Reference Area (ERA)				
Rentable Floor Area (RFA)				
If other, please declare				
Included Processes in Detail / Modules				
A1	Raw Material Supply	X	X	
A2	Transport to Manufacturer	X	X	
A3	Manufacturing	X	X	
A4	Transport to building site	(X)[5]	(X)	
A5	Installation into building	(X)	(X)	
B2	Maintenance	(X)	(X)	
B3	Repair	(X)	(X)	
B4	Replacement	X	X	
B5	Refurbishment	(X)	(X)	
C1	Deconstruction/ Demolition	X	X	
C2	Transport to EOL	(X)	(X)	
C3	Waste processing	X	X	
C4	Disposal	X	X	
D	Reuse, recovery or recycling potential	(X)	(X)	

5 The brackets mean that these activities are included only when there is data available.

3.3.4 Comparability of data and results

In overall, besides defining the building components and life cycle processes to be included in the analysis, the character of the indicators used for the quantification of the embodied impacts and the data sources used for determining the different energy and emissions factors, also other parameters need to be specified in order the results of different case studies to be comparable. The minimum documentation requirements are presented in Table 3.7.

Table 3.7 Main parameters for the description of a case study (Source: Subtask 1 report)

Parameter	Description of the Characteristics of the Object and its Assessment
Location /climate and or heating degree days / cooling	e.g. Germany/ moderate climate
Building/ Usage type / intensity of use	school building, 200 students, hours of operation 08.00 –18.00, includes a sport hall
Energy-standard	(“net positive” during the use phase, expressed in “primary energy equivalents”)
Gross floor area/ Net floor area	e.g. 726 m^2/ 615 m^2
Gross volume/ Net volume	
Reference area for EE/EC	e.g. energy reference area … 535 m2
Construction method	e.g. Structural steel frame supporting precast concrete floor slabs
U-values of the building envelope	
Ventilation system	
Heating and cooling system	
Final energy demand electricity	Appliances, lighting, services, etc. (kWh/m2a)
Final energy demand for heating and hot water / energy carrier(s)	(kWh/m2a)
Final energy demand for cooling	(kWh/m2a)
Purpose of assessment	e.g. to determine the energy and GHG emissions offsetting, when a net zero concept is applied
Assessment methodology	e.g. according to EN 15978:2011 guidance
Reference Study Period	e.g. 50 years
Included life cycle stages	e.g. cradle to handover (use a checklist, as the one shown in figure 3, to describe in detail which modules/ processes are included
Included parts of the building	e.g. use a checklist, as the one shown in figure 4, to describe in detail which parts of the building are included
Scenarios and assumptions used for construction process stage	....
Scenarios and assumptions used for use stage	....
Scenarios and assumptions used for EOL stage	e.g. recycling at the end of life
Databases used (if any)	e.g. KBOB-recommendation 2009/1:2014, ökobau.dat or EPD of program ...
Other data sources	e.g. EPD’s from manufacturers
LCA Software used (if any)	e.g. LEGEP
Method of materials quantification	e.g. BIM Architecture
Name/type of the indicator(s) used	use table 4 for reporting the character of the indicator used
Additional indicators assessed	

4. Evaluation methods for EE and EG

4.1 Calculation Methods and Databases

4.1.1 Outline of Databases

The embodied energy and embodied GHG emissions for a product or project are calculated by summing up the energy consumed and/or the GHG emissions for individual processes or material components that constitute the creation of that product or project across the included life cycle phases. Depending on the purpose and scope of analysis or evaluation, the required level of detail, the acceptable level of uncertainty, and the available resources (data, time, human resources, know-how and budget), the primary datasets are calculated using one of these three methods:

- Process-based life cycle assessment
- Environmentally extended Input-output (I-O) analysis, and
- Environmentally extended Hybrid analysis, which combines the two above methods.

The choice usually depends on the purpose and scope of the task, the required level of detail (information on single technological processes or aggregated entities), the acceptable level of uncertainty, and the available resources (data, time, human resources, know-how and budget). All these methods have been used in life cycle assessment (LCA) and embodied impacts assessment in building and construction.

The first two methods have different starting points for primary data sources. The process-based methodology is based on data and information in the process of manufacturing of a specific product or product class, from raw material extraction to production (if cradle-to gate), and thus, is often referred to as a “bottom-up” approach. The I-O approach is based on national I-O tables of economic activity across industry sectors (aggregated but comprehensive information), and is thus, often referred to as a “top-down” approach. Details of the technical basis and the procedural steps for each of the three methods are presented in the next section.

The embodied impacts quantification process follows the LCI approach setting the system boundary, identifying the system inputs and outputs, and estimating the total energy and CO_2 emission of the system. Table 4.1, Table 4.2 and Table 4.3 summarize the key characteristics of each method and each database.

Table 4.1 Summary of different embodied impact calculation methods (Source: Subtask 3 report)

Method	**Process method**	**IO analysis**	**Hybrid analysis**
Guideline/Standard etc	ISO 14040, ISO 14044, ISO/TS 14067 UNEP SETAC ISO 21930, EN 15804, EN 15978 PEF guide ({European Commission, 2014 #4937}) etc	UN UNEP ({UN, 2000 #5301})	No guideline but similar to "process method" except for granular level of data (IO data used for granular level)
Data input	Company data Associations data Industrial data (statistics) Public authorities data (e.g. road transport emissions and energy consumption), energy and environmental performance of power plants, waste incinerators etc.) Scientific publications	National statistics on annual sectorial production (physical and monetary), imports, exports, investments and consumption National statistics or information on intersectorial purchases and delivery of intermediate products and services National statistics on annual emissions and resource consumption, Allocation of the national emissions and resource consumptions to the economic sectors.	Process data LCI data Economic data Economic input-output data
Data output	CO_2, MJ etc per product or building based	kg CO_2, MJ etc per monetary based ($)	CO_2, MJ etc per product or building based
Calculation approach	Matrix inversion or sequential accumulation	Economical input-output matrix inversion	Combined "Process" & "IO" methods
Examples	ICE, ecoinvent (see e.g., {Frischknecht, 2004 #1840}, etc.	3EID, Carnegie Mellon EIO LCA, CREEA ({Tukker, 2014 #5298}) etc	Scientific papers from universities
Note	Detailed granular level (i.e., material, product building, etc) Does usually not cover service sector inputs such as building insurance, planning processes and the like.	Can cover macro level (building, urban, industry etc) usually covers all economic activities, including financial services, planning services, advertising and the like	Combined process and IO approach.

Table 4.2 Existing databases and their characteristics 1 (Source: Subtask 3 report)

Database	Geographical Boundary	Unit	Coverage	Primary data source	Lifecycle boundary	Method	Standardization
3EID (Embodied Energy and Emission Intensity Data)	Japan	TOE or Ton-C/ ¥	EE/EG	Japanese Economic Input-Output data	Cradle to gate	Input-Output	N/A
ICE	UK/Europe	kgCO2e/SI unit (kg, m2 etc)	EE/EG	journal/books/conferences etc.	Cradle to gate	Process	ISO 14040/44
E3IOT	Europe	Emissions/€	LCI	European Economic IO data	Cradle to gate	Input-Output	N/A
Athena LCI	N.A. (Canada)	Emission/SI unit (kg, m2 etc)	LCI	Industry	Cradle to gate	Process	N/A
Carnegie Mellon EIO LCA	N.A. (US)	t-CO2/$US	LCI/EG	US Economic IO data	Cradle to gate	Input-Output	N/A
US Embodied energy	N.A. (US)	Lbs CO2/ft2	EE/EG	Athena data	Cradle to grave	Process	N/A
FWPA	Australia	CO2eq/SI unit (kg, m2 etc)	EG	ecoinvent	Cradle to gate	Process	ISO 14040/14048
BPLCI (Building Product LCI)	Australia	Emission/SI unit (kg, m2 etc)	LCI	ecoinvent	Cradle to gate	Process	ISO14044
NZ EE/EC data	New Zealand	$	EE/EG	New Zealand Economic IO data	Cradle to gate	Input-Output	N/A
Ökobau.dat	Germany	Emission/SI unit (kg, m2 etc)	LCI/A	Gabi database	Cradle to gate	Process	EN15804
ecoinvent data 2.2+	Switzerland	Energy resource/SI unit; Emission/SI unit (kg, m² etc)	LCI (unit process and cradle to gate), LCIA/EE/EG	ecoinvent data v2.2+	gate to gate and cradle to gate	Process: underlying data accessible on unit process level	compliant with all relevant international standards
KBOB recommendation 2009/1:2014	Switzerland	Energy resource/SI unit; Emission/SI unit (kg, m² etc)	LCA/EE/EG	ecoinvent data v2.2+	manufacture (cradle to gate) & disposal	Process: underlying data accessible on unit process level	compliant with EN15804
GIOGEN (LCI database for civil works)	France	Emission/SI unit (kg, m2 etc)	LCI	ecoinvent	Cradle to gate	Process	N/A

EE: Embodied energy, EG: Embodied GHG, LCI: Life cycle inventory

Table 4.3 Existing databases and their characteristics 2 (Source: Subtask 3 report)

Methods	DB	GHG other than CO2	Recycled/ Reused	New Material	Equipment	Imported	Transportation	On site emissions	Waste treatment
Process	Australiasian	✔□	✔□	–	–	–	✔□	✔□	–
	BUWAL250	–	✔□	–	–	✔	✔□	✔□	✔
	ecoinvent	✔□	✔□	–	–	✔	✔□	✔□	✔
	KBOB2014	✔□	✔□	✔□	✔□	✔□	✔□	✔□	✔□
	ETH-ESU96	✔□	✔□	–	–	–	✔□	✔□	–
	FranklinUSA98	–	✔□	–	–	–	✔□	✔□	–
	IDEMAT	✔□	✔□	–	–	–	✔□	✔□	–
	Boustead	–	✔□	–	–	–	✔□	✔□	–
	ICE	✔□/-	✔□	–	–	–	✔□	✔□	–
	CLCD	✔□	✔□	–	–	–	✔□	✔□	–
	KLCI	✔□	✔□	–	–	–	✔□	✔□	–
	GreenBookLive	N/A	N/A	✔□	–	✔□	✔□	✔□	–
	USLCI	✔□	✔□	–	–	–	✔□	✔□	–
	FWPA	✔□	✔□	–	–	–	✔□	✔□	–
	BPIC LCI	✔□	✔□	–	–	–	✔□	✔□	–
	Aus LCI	✔□	✔□	–	–	–	✔□	✔□	–
	IVAM LCI	✔□	✔□	–	–	–	✔□	✔□	–
I/O	3EID	✔□	–	–	✔□	✔□	✔□	N/A	–
	E3IOT	N/A	–	–	✔□	N/A	✔□	N/A	–
	CenSA	✔□	N/A	–	✔□	✔□	✔□	N/A	–
	USA I/O	✔□		–	✔□	✔□	✔□	N/A	–
	AU I/O	–	–	–	✔□	✔□	✔□	N/A	–
	Danish I/O	–	–	–	✔□	N/A	✔□	N/A	–
	Korean I/O	–	–	–	✔□	N/A	✔□	N/A	–

4.1.2 Minimum requirement of Databases

(1) Minimum Requirements on EE and EG databases

The scope of EEG databases to be used in the construction sector should cover the following areas:

- civil engineering works,
- construction materials,
- building technologies,
- energy supply,
- transport services,
- waste management services

With processes from these economic sectors fairly comprehensive life cycle inventories of buildings and construction works can be established. The category “civil engineering works” may contain data on excavation of the trench and groundwater control during construction. The category “construction materials” should include mineral materials such as concrete or bricks, metals such as construction steel or aluminum, plastics used in piping and the like, renewable materials such as wood and further materials but also simple building elements such as doors and windows. The category “building technologies” contains rough and average LCI data on electric, sanitary as well as energy supply and ventilation equipment. These data are usually provided on a per m^2 usable surface basis. The energy supply data and the transport services data are used in modeling the use phase of buildings and the waste management services data help quantifying the end of life treatment of buildings.

The data provided in an LCI and more specifically EEG database should adhere to the following six basic requirements:

- Materiality: the LCI database should cover the most significant construction materials and building technologies, whereby significant is meant in terms of cost, mass, and expected environmental impacts (embodied energy and greenhouse gas emissions). Within the life cycle inventories of the individual construction materials, the relevant input and output flows must be covered. In the life cycle inventory of the manufacture of a refrigerant such as HCFC and CFC during production must be included (see e.g. (McCulloch and Campbell, 1998, cited in Frischknecht (2000)).
- Consistency: the life cycle inventory analysis of all construction materials follows the same modelling principles, apply the same system boundaries and cut-off criteria. The database protocol mentioned above helps in fulfilling this requirement. For instance, administration and marketing efforts should be excluded from the inventory analysis. Packaging efforts should be included if relevant.
- Transparency: A trustworthy EEG database allows for an access to the unit process data. This transparency enables the user to independently check the data quality of the underlying data and complies with the true and fair view requirements known from financial reporting. The user is able to adjust data if required or appropriate and the user may identify energy and climate

change hot spots in the supply chain of the building analysed. In most cases and areas data confidentiality is not an issue (energy supply data, waste management data, transport data) or may be overcome by horizontally or vertically aggregating company specific information. An opinion paper on data transparency in the EEG and LCA context can be found in Frischknecht (2004).

- Timeliness: The age of a dataset provided in an LCA database is determining its quality. But there is no fixed number of years determining whether or not a dataset may still be used. Depending on the speed of the technological development related to the production process of a construction material such as bricks, datasets may be rather old but still appropriate. In fast developing sectors such as photovoltaics however, the data update cycles should be significantly shorter (a few years only).
- Reliability: Are the data used to establish a dataset sourced from reliable information sources? Is the available information critically discussed and benchmarked with other sources of information? Are the figures finally chosen well substantiated?
- Quality control: Datasets offered in an LCA database should undergo an independent and external verification or critical review. Such a quality control process should be based on a review protocol. The duties and responsibilities of the reviewing experts should be clearly defined. The ecoinvent datasets v1 to 2 underwent a review which comprised the following main five steps:

(1) completeness check: are all files and information available?
(2) observance of protocol: does the work follow the requirements described in the protocol?
(3) plausibility check: do the data and their respective LCA results make sense?
(4) completeness of flows and impacts: does the dataset include all relevant elementary flow and thus is able to cover all relevant environmental impacts related to the product analysed?
(5) mathematical correctness: are the data computed correctly (e.g. from annual flows to per kg flows, conversion from kcal to MJ, from ft^2 to m^2)?

(2) Example of Database and its application

The KBOB-recommendation 2009/1:2014 is one example of an easy to use LCA database for architects and engineers (Figure 4.1).

It provides essential “building blocks” (“Lego® bricks”) required to establish a life cycle assessment of a building, namely LCA data on construction materials, building technology components, energy supply, transport services, and waste management services. With these data and supporting planning software used in the construction sector, construction, use and end of life of buildings can be assessed rather easily. When establishing LCA databases to be used in the construction sector, the tasks and responsibilities should be divided according to the expertise and availability of information. LCA data on construction materials such as sawn wood should be provided by LCA and domain experts. Software providers will embed these data into their planning tools and establish datasets on building elements such as prefabricated, insulated wood wall elements. Finally, the architect and engineer will model his or her building using predefined building elements available in the planning software tool.

While the PDF-version of the KBOB-recommendation is appreciated by architects and planners in discussions with clients and authorities, the Excel-version is key to transfer the information into software tools and finally to enable their broad application in the daily work.

LCA databases tailored for the construction sector should address the environmental relevant indicators, i.e. the ones required by national labelling and certification schemes. As long as the underlying life cycle inventory data are not restricted to energy demand and greenhouse gas emissions, they are suited to support a variety of environmental impact category indicators (see Figure 4.2) such as the indicators required by the product environmental footprint recommendation of the European Commission (2013) as well as single score indicators such as the eco-points 2013 based on the ecological scarcity method (Frischknecht and Büsser Knöpfel, 2013; 2014).

A flexible and comprehensive life cycle inventory database forms a highly valuable basis for many different applications (see Figure 4.3). For instance, the ecoinvent data v2.2+ (2014) forms the basis for the KBOB-recommendation 2009/1:2014. The contents of the recommendation in turn are used in several planning tools of the construction sector as well as in many Swiss technical bulletins and standards. Finally, labels and certification schemes make use of the technical bulletins and their underlying data to foster environmentally friendly buildings and construction works.

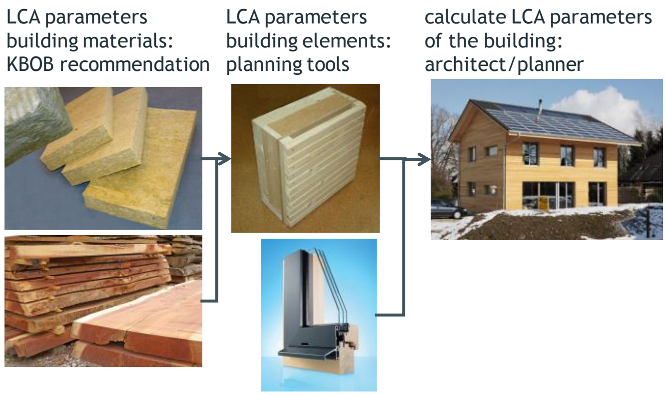


Figure 4.1 Division of tasks between LCA analysts, building software providers and architects/planners (Source: Subtask 3 report)

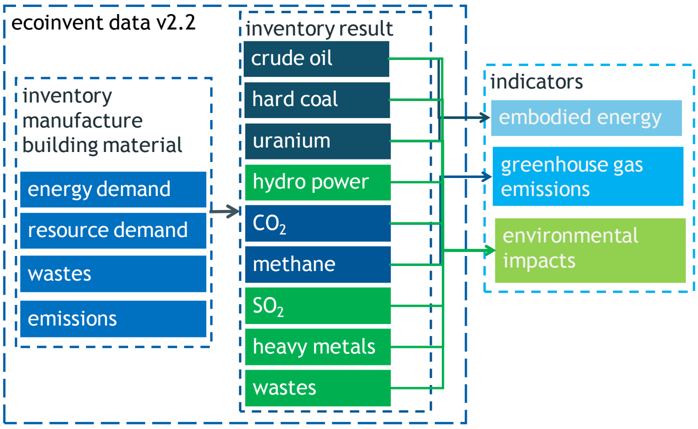


Figure 4.2 Connection between the unit process inventory data (left), life cycle inventory results (centre) and environmental indicators (right), shown on the example of the KBOB-recommendation 2009/1:2014)

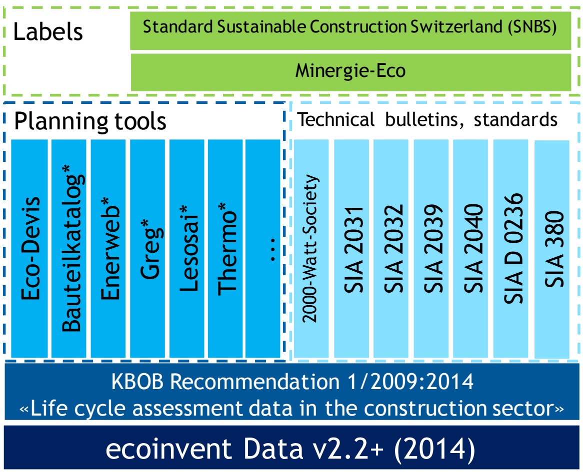


Figure 4.3 The comprehensive life cycle inventory database ecoinvent data v2.2+ forms the basis for the KBOB-recommendation 2009/1:2014), as well as several Swiss planning tools and technical bulletins and standards

4.1.3 Characteristics of Databases

(1) Process based Databases

The process based LCA subdivides the product/building system into a foreground system, for which primary data are collected and a background system, for which generic data are being used (see UNEP SETAC 2011).

The process based method may apply cut-off criteria to establish the system boundary (ISO 14040 and 14044). The international LCA standard proposes to use either a mass, energy or environmental impact criterion. Inputs that contribute less than a defined minimum share of mass, energy or environmental impact can be neglected and thus be excluded from the analysis. Construction sector specific standards further refined these criteria. The European EPD standard on construction products allow to neglect mass or energy contributions below 1 % as long as in total not more than 5 % of total mass or energy inputs are excluded (EN 15804).

The process method applied on buildings requires data on the mass of material and the m2 of walls/floors and the like used in a building. This information is known to the planners and architects as they need exactly this information to write the call for tenders for the construction companies. In particular with regard to building services such as ventilation systems or electrical systems, generic LCI data are derived from several case studies (ICE for European countries, Athena LCI data for North America, BPIC LCI data for Oceania, KBOB-recommendation 2009/1:2014 for Switzerland) to reduce the workload for the analysis of a particular building.

As general life cycle inventory analysis shown in ISO 14040 (2006), process analysis collects all material bill of quantities for the targeted product or building. The data consists of weight, volume, area and thickness etc. Then it converts into the embodied energy or embodied GHG emissions unit under the system boundary of target using existing LCI data. The system boundary comprises four individual stages of the life cycle ("Product", "Construction", "Use" and "End of Life" as shown in Figure 3.1and module boundary ("Raw material supply", "Transport", "Manufacturing" within the "Product" stage as shown in Figure 3.1.

Under the system boundary, the data needs to collect. As data collection has proven to be a time consuming process, not all data can be collected. It was therefore pertinent, given the time and other project constraints, to be specific about the data requirements.

To calculate the embodied energy and GHG emissions, the manufacturing process needs to be understood for various products through modelling of their process of manufacture, from raw material extraction to manufacturing. Details of direct and indirect feeds into the entire process are accounted for by allowing for a highly complex web of processes that together form a particular product. Figure 4.4 shows a typical process flow for dry process bagged cement used for mortar.

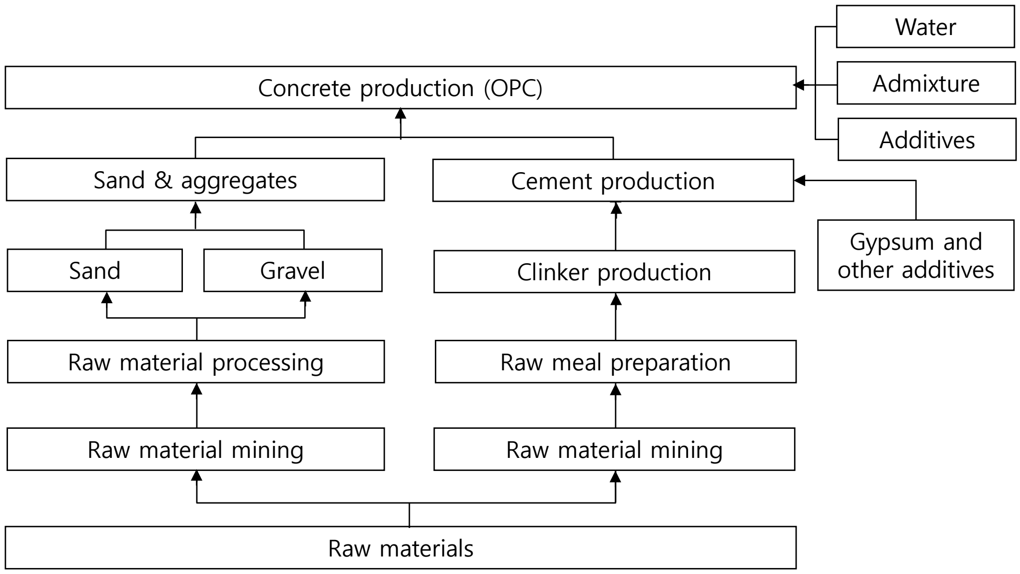


Figure 4.4 Process map for OPC (Source: Subtask 3 report)

(2) Input-Output based Databases

Input Output (IO) method is a top-down economic approach which uses sectoral monetary transactions data (national input output data) to account for the complex interdependencies of industries in modern economics (Treloar, 1998, Arpad, 1997; Flores, 1996). By linking this with statistical information on environmental exchanges for the same sectors, energy consumption or CO_2 emission intensity of a given product can be calculated. The I-O-based intensities are obtained as the averages of relevant industrial sectors. In the U.S. or Canadian I-O table, the number of industrial sectors reaches nearly 700, thus enabling detailed analyses to be conducted. On the other hand, that of the South Korean or Japanese I-O table is approximately 400. For other countries such as Thailand, Australia and Denmark, the number falls down between 100 and 200, yet it is still effective in calculating intensities. However, in the remaining countries where the recognized industrial sectors are 60 or less, the building sector and the civil engineering sector are handled together as the construction sector.

There are two proposed models of I-O tables: the symmetric model and the make-use model. The former focuses on the outputs of industrial sectors. The latter consists of a make table (containing the output of an industrial sector as well as the outputs as products of the same industrial sector) and a use table (listing commodities consumed by each industrial sector). Japan, South Korea and Switzerland use the symmetric model, while countries such as the U.S. and Canada use the make-use model.

Even if there are several hundred of industrial sectors available, those related to buildings are narrowed down up to 200 industrial sectors. Thus, it is difficult to obtain intensities relative to building materials in detail. However, the materials mainly used in buildings are those making up the major components such as steel, concrete and cement products.

The requirements for estimating I-O-based intensities regarding buildings are (i) at least in the construction sector, building and civil engineering should be handled as separate industrial sectors, (ii) the number of industrial sectors in I-O tables should be 150 or more, and (iii) relevant data should be available for allocating energy consumption and CO_2 emissions to the economic sectors. Therefore, it is not possible to calculate I-O-based intensities for every country in the world.

EEG intensities for new materials have both advantages and disadvantages. As an advantage, from its price and manufacturing type, the EEG of a new material can be roughly estimated using I-O tables. However, as a disadvantage, the industrial sector which is responsible for manufacturing of the new material often manufactures other products as well, and therefore, it is difficult to obtain only the EEG of the new material.

(3) Hybrid Databases

Hybrid method combines the strengths of both methods (process and I-O methods) using as many specific process data as possible, while covering the remaining system with average IO data. The hybrid method either starts with the complete system and adds process data that make manufacturing processes explicit or it starts from a process LCA and adds inputs which are not quantified on a process level. Also, the hybrid method combines many of the weaknesses of the process and I-O methods. The cost of the hybrid method can be as large as that of the process and the I-O methods, as the hybrid method is aimed at achieving best quality and highest level of comparability in the estimates. The quality of the hybrid method also depends on the availability and quality of primary and secondary data in both the process method and the I-O table.

(4) Comparison

Background process based LCA databases on building materials, building services, energy supply, transport and waste management services serve a similar purpose like the environmentally extended economic input output tables. They both help reducing the effort to quantify the embodied energy and embodied GHG emissions of buildings.

To establish background process based LCA databases is similarly time consuming like to establish environmentally extended input output databases. The system boundary and cut-off criteria, the availability of company or sector specific reliable and transparent data are main challenges with regard to process based LCA data. Further challenges are related to construction products manufactured abroad, where data availability is often limited. Services such as planning (architects' work) are often not taken into account in process-based LCA. However, they often play a negligible role compared to the embodied energy or CO_2 of the construction of a building.

The proper assignment of energy consumption and GHG emissions to the economic sectors of a country (and to the public and private consumption), the quantification of the inter-sectoral supply and demand and the assignment of imports to the economic sectors and the quantification of their energy demand and GHG emissions are the main challenges with regard to environmentally extended input output tables. Price levels, inflation and fluctuating exchange rates are further challenges.

If a reliable and sufficiently complete background LCA database and if a reliable and sufficiently environmentally extended I-O table is available, the two approaches (process based and I-O based) do not differ substantially in effort to assess the embodied energy or GHG emissions of a particular building.

Table 4.4 Comparison of EE data for building products with different methods (Source: Subtask 3 report)

Material	Process based LCA*	Hybrid**	IO***
AAC block	3.5	4	6.8
Aluminum	154.3	252	378
Appliances	301.1	250	301
Brick	8.2	3.3	5.4
Carpet	74.4	288	212
Ceramic tiles	9	22	32
Roof tile (clay)	6.5	20	17
Concrete	1.1	1.8	2.4
Concrete pavers	2	3.2	3.2
Concrete tile	2	4.8	4.5
Door (solid)	23	74	74
Door (hollow)	23	48	48
Glass	13.5	168	83
Insulation (glass wool)	28	172	107
Insulation (reflective)	154.3	370	303
Mortar	1.3	1.8	2.6
Paint	80	284	194
Plaster	1.8	27.2	8.9
Plasterboard	2.7	7.4	27.2
Plastic	87	64	163.4

*CSIRO (2006)

**Treloar, 2006

***Foran et al., 2005

4.2 Specific issues to be considered at calculating EE and EG

4.2.1 Imported materials

Imported material/product should require tracking upstream for the energy sources used in the country of production, transport distances etc. Different countries have different electricity mix. And thus, it may influence misinterpretation of EEG results.

Figure 4.5 represents an example of embodied GHG emissions of aluminium for different countries. To manufacture of 1 kg of primary aluminum product, 11.2-21.5 kg of CO_2.

Like this, even though same product, the embodied GHG emission can vary depending on the different countries. Thus, it should be considered geographical characteristic of embodied GHG emissions, if it imported from abroad.

Imported material/product should be identified for their source.

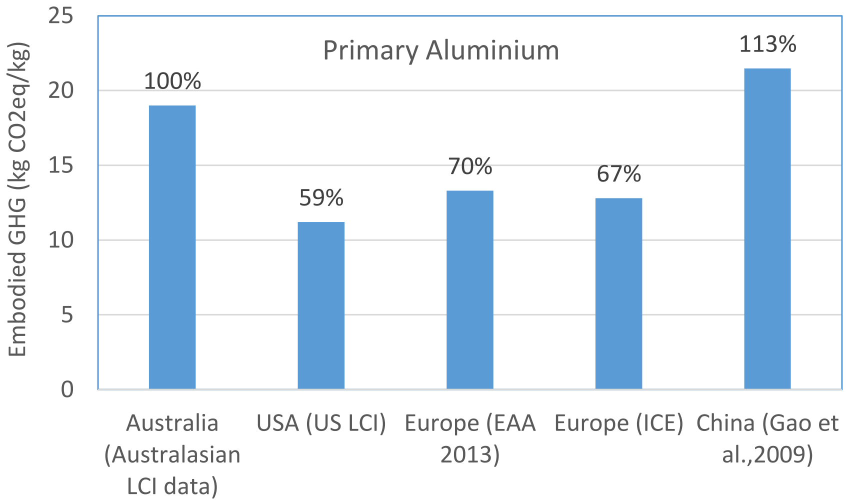


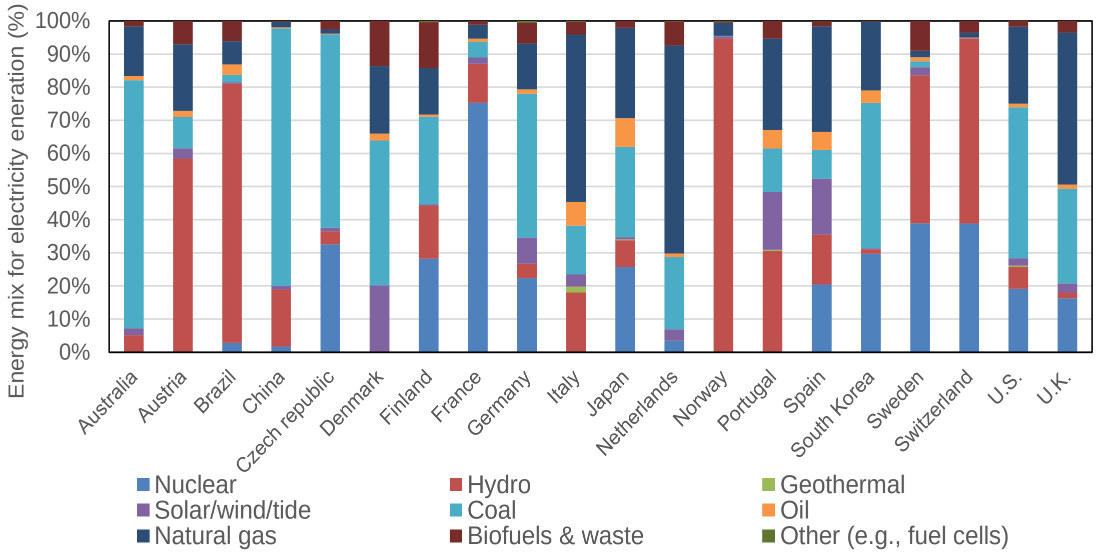
Figure 4.5 Embodied GHG emissions of Aluminium comparison for different countries (Source: Subtask 3 report)

4.2.2 Electricity supply mix

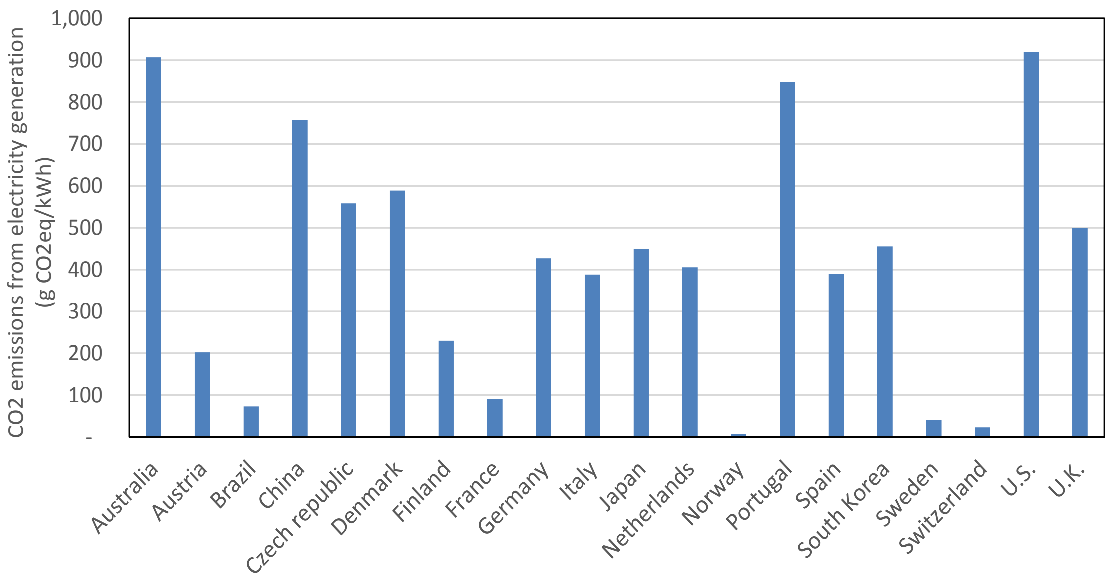
The electricity supply mix in different geographical areas and countries may have a significant effect on life cycle CO_2 emissions of construction materials and finally the embodied carbon of buildings. Figure 4.6 shows, for example, the different electricity mixes in selected countries. Electricity generation in Australia is predominantly from coal burning, while in the UK it is from natural gas. In both the US and Japan, it is primarily from oil burning. This difference in energy mix ((a) means different GHG intensity for power, and thus, emissions total (b)).

The latter shows that in Australia it takes 0.891 kg of CO_{2eq} to generate 1kWh of power. In the UK it is 0.557 kg of CO_{2eq} per kWh (only 63% of Australia's) and in Japan it is 0.365 kg of CO_{2eq} (less than 41% of Australia's).

In calculating embodied energy and GHG emissions, this means that it is very important to use the appropriate energy mix for a given product in a particular country, and to report what reference energy mix has been used.



(a) Energy mix for electricity generation in different countries (IEA, 2012)



(b) GHG intensity of electricity generation for different countries (IEA, 2009)

Figure 4.6 Energy mix for power generation and GHG emissions for selected countries (Source: Subtask 3 report)

4.2.3 Fluorocarbon

Many existing embodied GHG emissions studies for building show ignoring the GHG release/leakage emissions or assume it to be negligible. However, these GHG emissions are not small. It should be taken into account for embodied or life cycle GHG emissions of building.

There are four different types of fluorinated gases:

- Hydrofluorocarbon (HFCs)
- Perfluorocarbons (PFCs)
- Sulphur hexafluoride (SF6) and
- Nitrogen trifluoride (NF3)

Of these, HFCs influence most the GWP from buildings. Due to the Montreal protocol, CFCs have been banned from the industry and HFCs, as an alternative to CFCs, have been used in buildings, such as a blowing agent of insulation material and refrigerants for cooling systems in buildings. This chapter introduces the release or leakage of HFCs used in insulation materials and refrigerants in buildings.

Figure 4.7 shows the result of embodied GHG emissions between when considered CFCs release from insulation material and leaks from A/C from the example building in the initial construction phase (cradle to construction site) and over the life cycle (cradle to grave over the 60 years). Initial embodied CO_{2eq} emission is quantified 0.65 ton CO_{2eq} from cradle to construction site when CFCs release and leaks are not considered from the insulation material and building. On the other hand, when considered these emissions, embodied CO_{2eq} emissions increase 0.71 ton CO_{2eq} per m2 of building, which is increases 10% more. When considered the embodied CO_{2eq} emissions during the life cycle of building (60 years in this case), the difference of GHG emissions between in the both cases (consideration or not consideration of CFCs from insulation material and leaks from A/C) shows much higher. As shown in Figure 4.7, total embodied GHG emissions show 1.30 ton CO_{2eq} per m^2 when CFCs emissions are not considered (w/o CFCs in Figure 4.7). But when considered these emissions (w/ CFCs in Figure 4.7), the total embodied CO_{2eq} emissions increase 41% more (1.84 ton CO_{2eq} /m^2) for w/o CFCs' case. This is due to contribution of CFCs leaks (0.41 ton CO_{2eq} /m^2) from A/C of building and CFCs release (0.12 ton CO_{2eq} /m^2) from insulation material in the example building.

As shown in this case, the embodied GHG emissions can vary depending on the CFCs consideration.

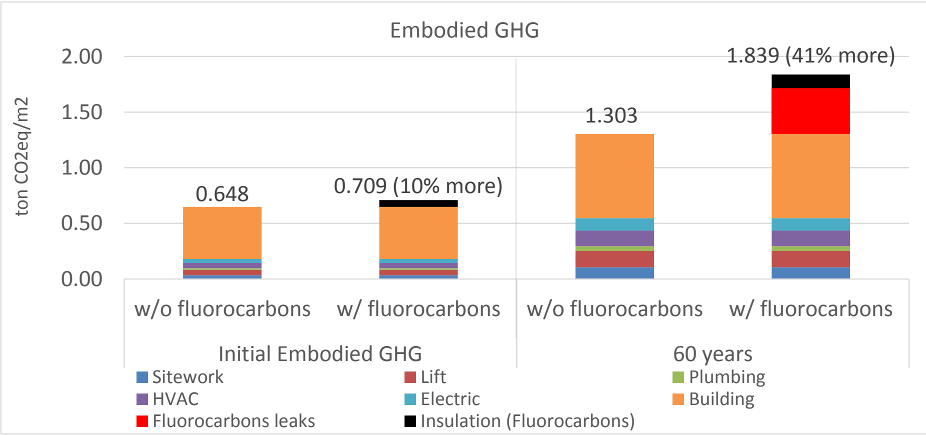


Figure 4.7 Embodied GHG emissions of example building (Source: Subtask 3 report)

4.2.4 Transportation

Transportation is required energy and GHG emissions to deliver the product from manufacturing site to construction site (A4 in Figure 3.1) and building site to waste processing site (C2 in Figure 3.1). Embodied energy and GHG emissions cover these energy consumption and GHG emissions. The transportation distance of material/product from the manufacturing site to construction site or building deconstruction site waste processing site is not always homogeneous and varies depending on the place and situation. In many cases (Lemay, 2011; Seo and Hwang, 1998, Junnila and Horvath, 2003; Hendrickson and Horvath, 2000), this is also ignored or assumed to negligible due to its relatively small proportion comparing to other life cycle stages, which considered embodied impacts.

4.2.5 Site works

EEG from the construction site comprises energy consumption and corresponding GHG emissions during the construction activities. These activities mainly include site preparation, structural installation, mechanical/electrical facilities installation and finally finishing for interior.

During these activities, power (tools and lighting etc.) and fuel (transport) are used in the construction site. Also, construction waste after installation of building products, elements, components is transported into waste management system (landfill, recycle center etc.).

Energy consumption (GHG emissions) of power tools or heavy equipment (e.g., cranes, generators, prestressing equipment, concrete pumps etc.) can be quantified using the converting electricity to energy units for power tools or the using the fuel consumption data of heavy equipment. However, it is not easy to get the data for running hours of tools or equipment. Thus, many studies assume the energy consumption and GHG emission from construction equipment are too small and thus it is negligible (Lemay, 2011; Seo and Hwang, 1998; Junnila and Horvath, 2000) or underestimated its impacts (Hendrickson and Horvath, 2000).

Many existing studies (Cole and Rousseau, 1992; Chen et al., 2012; Chen, 2011; Seo et al., 2014; Stein et al, 1976) assumes construction CO_2 emissions or energy to be (7%~12%) of the total embodied energy (CO_2) or ignore the CO_2 emissions from construction site due to the emission negligible comparing to another phase (Seo and Hwang, 2001; Hacker et al., 2008). Many existing studies do not show this clearly. It should be clearly described their boundary or report whether it considered or not.

4.2.6 Waste management

Over a building's life cycle, waste generates from construction phase on site, replacement of building components in the usage phase, and deconstruction phase when a building is removed or demolished.

It is reported that key waste stream which influenced GHG emission for construction waste is mixed packaging and plastics having 10% of total waste and mixed construction waste (63%) (BAM, 2014). Most of CO_2 emission from construction waste management comes from embodied GHG emissions of material itself.

It is estimated about 4% of in-situ concrete goes to waste from the construction site (WRAP, 2014). Due to the over-order and mishandling of products at the site, roughly 20% of bricks are wasted on site. Metals and timber, which are key building materials, are also 10% goes to waste on site.

4.2.7 Recycle/Reuse materials

To reduce energy, GHG emissions and limited resource, building is highly recommended to use more recycled or reused materials for their construction. Manufacture of building product with virgin materials fundamentally requires more processes. It means, the more processing required producing the material or product, the higher energy and GHG emissions release. For materials such as virgin (primary) steel or aluminum, the embodied GHG $emissions_2$ is much higher than that of recycled ones as much more energy is used in the extraction process from ore than from recycled one.

Figure 4.8 shows an example for aluminum window. To manufacture of $1m^2$ window with primary aluminum material, 43.4 kg of CO_2 is quantified. To reduce the GHG emission, various recycled aluminum products can be considered for window from 10% to 30%.

Figure 4.9 show an example for steel. The crude steel (converters) is highest impact because it uses virgin iron ore. The Crude steel (electric furnaces) shows small impact because it uses mainly recycled steel. The Hot rolled steel shows middle impact because it shows average of steel products value.

This is not only for aluminum products and steel products but also can be find in the other building material or components, such as concrete, timber etc.

In the preliminary survey for EEG of recycled (reused) material (see Subtask 3 reports), very few countries consider recycled or reused materials for their analysis of building. However, there may not be always available data for recycled/reused materials. Thus, it should be clarify this in the limitation or assumption in the quantification study.

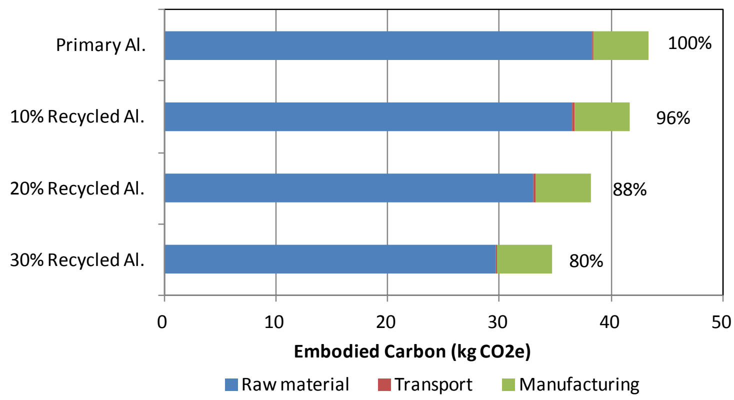


Figure 4.8 Embodied GHG emissions comparison between different recycled aluminium for window (Source: Subtask 3 report)

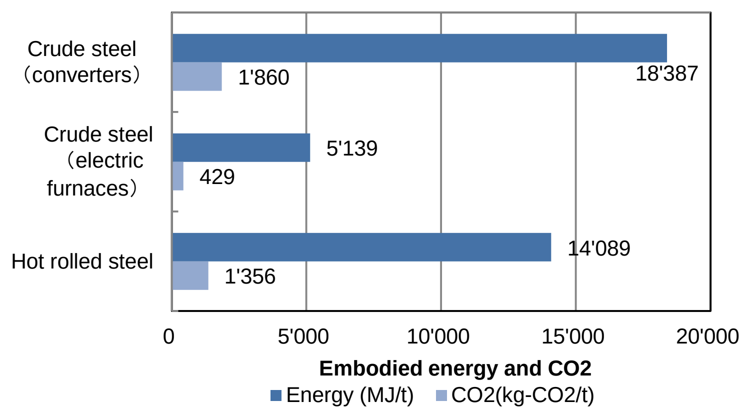


Figure 4.9 Embodied energy and GHG emissions of Steel (Source: Yokoyama, K., 2015)

4.2.8 Service life

Service life is another key consideration which influences to total EEG for building. Particularly service life is directly relevant to recurring embodied energy/ GHG emissions, which is energy consumption or GHG emissions due to maintain, repair, refurbish or replace material, components/system of building's life. The longer the service life of a building material, the less the quantity of material required for maintenance or repair for building. Thus, the longer service life of building material directly influence to less embodied energy or GHG emissions (recurring) due to maintenance or replacement of building's life.

Figure 4.10 represents initial and recurring EE for the example building. The initial EE (which is not related to service life) was 4.1 GJ/m^2. The recurring EE varied depending on the service life of the components. With minimum service life of components, recurring EE was 23% of the initial EE. Timber windows and internal walls contributed greatly to the recurring EE, accounting for 59% of the total recurring EE. On the other hand, with maximum service life of components recurring EE was only 1.9% of the initial EE of the building. This case study shows that durability and service life of building components can significantly influence the total EE. Thus, there should be careful consideration of service life of building components to reduce EE.

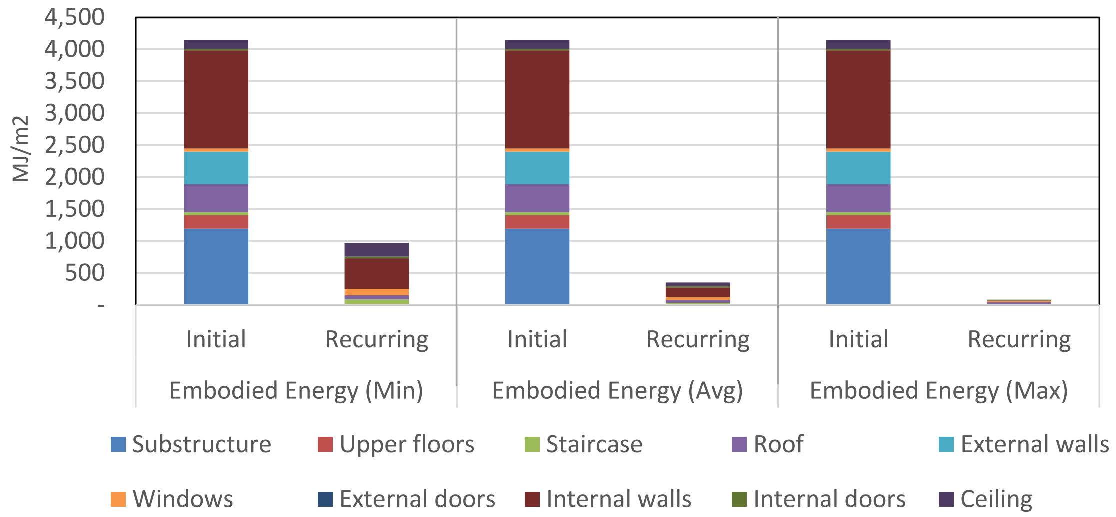


Figure 4.10 Embodied energy of residential building for a 50years life span (Source: Subtask 3 report)

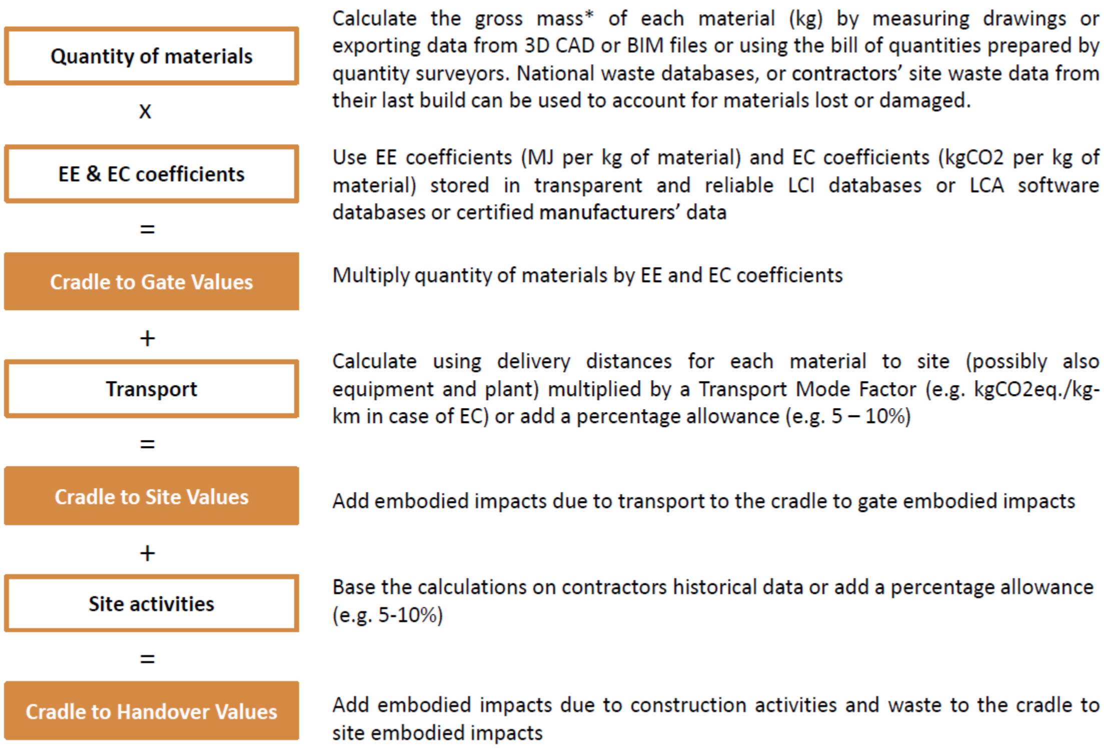
4.2.9 New materials and systems

For building construction, new or emerging products can be applied. But many EEG studies assume common product and used to generic EEG data. This is because mainly limitation of EPD data of new/emerging data. Industry tends not to open their data for confidential issue. In the survey of each country (see Subtask 3 reports), no respondents to consider emerging products for their EEG quantification. One of the key reasons is data limitation (not available). Thus, most of studies assumed to be common data for emerging product unless EEG data available (e.g., EPD).

4.3 Calculation procedure

4.3.1 *Outline of calculation procedure*

The first step is to calculate the total quantity of different materials and then multiply each by the relevant Embodied Energy (EE) and Embodied GHG emissions (EG) coefficient – often derived from databases (details are provided later in this guidance) – to obtain cradle to gate values. To estimate the cradle to handover value, allowance must be made for site and fabrication wastage, transportation from the factory gate to the site and construction activities associated with installing the material or product. This can add between 5-20% of the total, depending on the type of materials used, where they are sourced from and the level of construction activity. All the values for each material or product are added together to give the cradle to handover values for the building. After calculating cradle to handover embodied impacts, Figure 4.11 shows the continuity of the calculation routine in order to obtain cradle to grave values of embodied impacts.



******quantities of some materials not always have to be converted into weights as their embodied energy and carbon factors are often provided in other units (e.g. per brick, per m^2 or kWh for PV modules, per m^2 for paints and carpets, etc.)*

Figure 4.11 Typical process to calculate cradle to handover values of embodied impacts (Source: Guideline for Designers and Consultants, Part1)

4.3.2 *Basic calculation procedure*

This approach to quantifying the EEG involves classifying the building into the building works or elements based on key components then quantifying the EEG using the impacts intensities (energy and GHG emissions). In this case, the EEG can be quantified using the existing impact intensity dataset for building products/elements and equipment etc. Table 4.5 represents a spreadsheet to quantify the embodied energy and GHG emissions based on the quantities of products and facilities' usage. This is for the initial embodied impacts quantification (cradle to construction site), while the whole embodied impacts over the life cycle are shown in Table 4.6.

Table 4.5 Calculation sheet (initial embodied impact) (Source: Subtask 3 report)

Item	Materials and equipment	Quantity	Unit	Embodied Energy (EE) Intensity	Embodied GHG (EGHG) Intensity	Initial EE	Initial EGHG
				MJ/Unit	kg-CO2eq/unit	GJ	t-CO2eq
	Materials	Quantity (eg., 10)	Kg (m3 etc.)	MJ/kg (m3 etc.)	Kg CO2eq/kg (m3 etc.)	GJ	ton CO2eq
Building (Envelope)							
Electric							
HVAC							
Plumbing							
Lifts							
Site work							
	a	*b*	*c*	*d*	*e*	*b x d*	*b x e*

Table 4.6 Calculation sheet (Life cycle) (Source: Subtask 3 report)

Item	Materials and equipment	Initial EE	Initial EC	Maintenance	Number of Times Replaced	Demolition	Lifecycle EE	Lifecycle EGHG
		GJ	t-CO_2eq				GJ	t-CO_2eq
	Materials	Quantity (eg., 10)	Kg (m3 etc.)	MJ (or kg CO2eq)/m2	Times/life cycle	MJ (or Kg CO2eq)/m2	GJ	ton CO2eq
Building (Envelope)								
Electric								
HVAC								
Plumbing								
Lifts								
Site work								
Total	*a*	*b x d*	*b x e*	*d*	*n*	*f*	*Total EE*	*Total EGHG*

(b x d)+ (d x n) + f = (Total EE)

(b x e)+ (d' x n) + f' (Total EGHG)

d: embodied energy for maintenance
d': embodied GHG for maintenance
f: embodied energy for demolition
f': embodied GHG for demolition

4.3.3 Simple calculation procedure

(1) Items for simple calculation and calculation sheet

In order to determine at an early stage of planning, it would be preferable to allow calculations that would identify equipment and materials contributing to the reduction of the EEG. Accordingly, the EEG shall be calculated focusing on the amount of materials and equipment by pinpointing in the building construction field where a great deal of energy consumption and GHG emissions would occur. Even in the basic design stage, when the building structure is determined, quantities of materials such as concrete, steel bars and steel frames shall also be fixed, and the area of openings could be obtained based on the exterior design. In terms of facilities, the type of heat source/capacity and air-conditioner capacity in the air-conditioning system could be obtained. Similarly, the capacity of a substation facility and the approximate number of lighting fixtures in the electrical installation may be obtained. The equipment and materials are total 18 items as shown in Table 4.7. The calculation table shown in Table 4.12 and Table 4.13 was prepared as a method for calculating the EEG according to the quantities of facilities and estimated costs thereof. Table 4.12 is a calculation sheet at the time of construction, whereas the one shown in Table 4.13 covers the entire lifecycle. The EEG shall be calculated by entering quantities and intensities in these tables.

Table 4.7 Materials and equipment for simple calculation (Source: Subtask 3 report)

Item	Name of materials and equipment		Unit	Description
Building	Structure	Concrete	Volume (m^3)	The estimate value of the capacity of the concrete
		Steel bar	Weight (t)	The estimate value of the weight of the steel bar and flames
	Outer wall finishing	Tile	Area (m^2) or Price	The estimate value of the area or price of tile
		Metal window frame	Area (m^2) or Price	The estimate value of the area or price of window flam and door.
		Insulation	Weight (t)	The estimate value of the weight of the insulation (polystyrene or urethane foam)
		Fluorocarbon	Weight (kg)	Amount of fluorocarbon contained in insulation. See Table 4.
	Internal finishing		Gross floor area (m^2)	It is assumed to be proportional to the gross floor area. A floor, door, ceiling and wall are included.
	Other work for building		Price	The estimate value of the price of other building work.
Electric	Equipment		Capacity (kVA) or Price	The estimate value of the capacity or price of transformer and switching gear.
	Lighting		Quantity	The estimate value of the quantity of the light fittings.
	Other work for electric		Price	The estimate value of the price of other electric work.
HVAC	Chillers		Capacity (kW) or Price	The estimate value of the capacity or price of chillers.
	Air conditioners		Capacity (kW) or Price	The estimate value of the capacity or price of air conditioners.
	Fluorocarbon		Weight (kg)	The estimate value of the weight of refrigerants for the chillers and air conditioners.
	Other work for HVAC		Price	The estimate value of the price of other air conditioning work.
Plumbing	Plumbing work		Price	The estimate value of the price of plumbing work.
Lift	Lift		Capacity (kW) or Price	The estimate value of the capacity or price of lift.
Site work	Temporary work, electricity bill		Gross floor area (m^2)	It is assumed to be proportional to the gross floor area. It is included temporary work, electricity bill

(2) Intensities and unites

Methods for calculating energy consumption and GHG emissions intensities may be based on the input-output analysis, the process based method, or the hybrid method combining the two. Therefore, depending on the user, the method of calculating intensities that the EEG calculation is based on may be selected according to individual discretion. For example, one may choose to use intensities based on the process-based method. Moreover, units shown in the Unit section should also be modified as necessary depending on the types of intensities.

(3) Fluorocarbon

Regarding fluorocarbon used as refrigerant for insulation or refrigerating equipment, the EE or EG may be obtained by calculating the amount of gas using estimated values and multiplying it by the GWP, which is relative to the emissions of carbon dioxide.

i) Amount of Fluorocarbon contained in insulating materials

Percentages of the Fluorocarbon content in major insulators are provided in Table 4.8.

ii) Amount of Fluorocarbon contained in refrigerant

Table 4.9 gives an indication of the percentage of the refrigerant content in refrigerators and air-conditioners. It also shows the amount of refrigerant leaking when used, and that recovered at the time of disposal. The GWPs of major refrigerants are listed in Table 4.10.

Table 4.8 Densities of insulators, types of Fluorocarbon and their content rates (Source: Subtask 3 report)

	Thermal conductivity W/(m·K)	Density kg/m^3	Type of Freon	GWP (-)	Fluorocarbon Content rate (%)
Expanded polystyrene	0.034	29	R-134a	1,430	2.7
Urethane foam (board-shaped)	0.028	30	R-245fa	1,030	4.7
Urethane foam (foamed on-site)	0.028	30	R-245fa	1,030	7.3

Table 4.9 Emissions factor and collection rate at the time of disposal by refrigerator (Source: Subtask 3 report)

<table>
<tr><th rowspan="2">Name of Equipment</th><th rowspan="2">Intensity of refrigerants [kg/kWth]</th><th colspan="2">CO_2 emissions factor</th><th>Recovery efficiency</th></tr>
<tr><th>IPCC Guideline [5]</th><th>Japan [6]</th><th>Japan [7]</th></tr>
<tr><td>Chillers</td><td>0.33</td><td>2%-15%</td><td>6%-7%</td><td rowspan="2">30%</td></tr>
<tr><td>Residential and commercial A/C including heat pump</td><td>0.33</td><td>1%-10%</td><td>2%-5%</td></tr>
</table>

Table 4.10 GWPs of individual refrigerants (Source: Subtask 3 report)

Name	GWP
R410A	2090
R134a	1430
R32	675
HFO1234ez	6

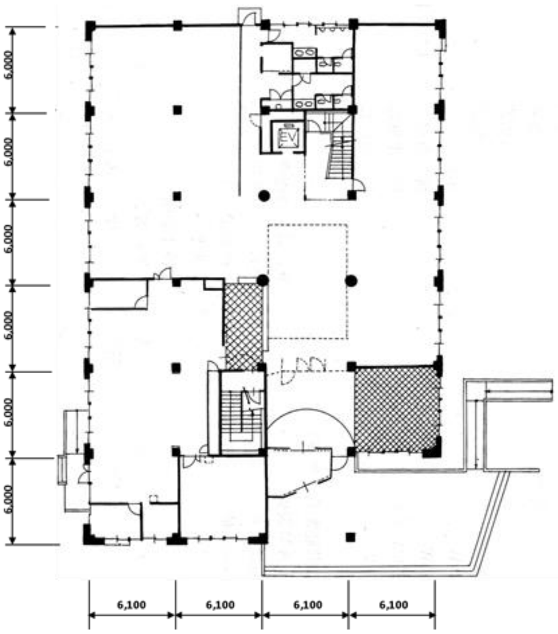
(4) Result of simple calculation in a sample building

Outline of the sample building

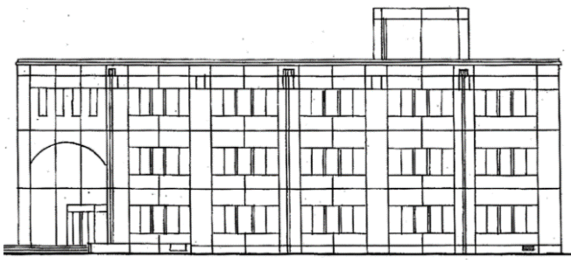
The library made of reinforced concrete indicated below has been selected as a sample building. The outline of the building is shown in Table 4.11 and Figure 4.12.

Table 4.11 Outline of the sample building (Source: Subtask 3 report)

Intended use	Library
Location	Japan
Structure	Reinforced-concrete
No. of stories	3
Site Area	849.37m^2
Gross floor area	2,412.99m^2
Electrical equipment	Receiving high-voltage electricity: 125kVA, Lighting and consents, Broadcast and telephone equipment, Disaster prevention system
Air-conditioning equipment	Air cooled chiller, Gas heatpump unit, FCU on each floor
Water supply and drainage sanitation	System for direct connection to water supply, Sanitary facilities, City gas equipment
Elevator facilities	750kg x 1 unit.



(a) Ground floor layout (BCI, 2004)



(b) East front view (BCI, 2004)

Figure 4.12 Ground floor layout (a) and east side elevation (b) of the sample building (Source: Subtask 3 report)

Intensities

The IO based database is used in in this sample calculation. Energy consumption and GHG emissions intensities were calculated using the 2005 input-output table and tables of values and quantities in Japan.

The intensities such as site work, interior finishing work and other work are obtained according to calculation results of 2 types of sample buildings.

Result of simple calculation

The EEG values at the time of construction are shown in Table 4.12 and results of the lifecycle (60 years) calculation are provided in Table 4.13.

Table 4.12 Result of Simple Calculation (Initial)
(Source: Subtask 3 report)

Item	Name of materials and equipment	Quantity	Unit	EE Intensity	EG Intensity	Initial EE	Initial EG
				MJ/unit	kg-CO_2/unit	GJ	t-CO_2
Building							
Structure	Concrete	1,729	m^3	1,295	267	2,239	462
	Steel bars	220	t	14100	1360	3,102	299
Outer wall finishing	Tiles	4.426	10^6Yen	54,376	3,500	241	15
	Metal window frames	13.256	10^6Yen	35,353	2,878	469	38
	Insulation	0.754	t	44,584	3,057	34	2
	Fluorocarbon	0	kg		1030		0
Internal finishing		2,413	m^2GFA	733	59	1,769	142
Other work for building		37.437	10^6Yen	26,500	2,100	992	79
Subtotal						8,845	1,038
Electric	Transformers	0.341	10^6Yen	21,509	1,727	7	1
	Switching boards	3.433	10^6Yen	22,878	1,780	79	6
	Lighting	557	Nos.	85.6	6.2	48	3
	Other work for electric	16.642	10^6Yen	26,500	2,100	441	35
Subtotal						575	45
HVAC	Chillers	8.440	10^6Yen	23,502	1,808	198	15
	Air conditioners	11.081	10^6Yen	23,502	1,808	260	20
	Fluorocarbon	26	kg		2,090		54
	Other work for HVAC	24.800	10^6Yen	26,500	2,100	657	52
Subtotal						1,116	142
Plumbing	Sanitary ware	1.299	10^6Yen	54,376	3,500	71	5
	Other work for plumbing	9.665	10^6Yen	26,500	2,100	256	20
Subtotal						327	25
Lifts		6.300	10^6Yen	28,735	2,359	181	15
Site work	Temporary work, electricity bill	2,413	m^2GFA	431	33	1,040	80
Total						12,083	1,344
per GFA	/m^2					5.008	0.557

Table 4.13 Result of Simple Calculation (Lifecycle 60 years) (Source: Subtask 3 report)

Item	Name of materials and equipment	Initial EE	Initial EG	Maintenance	Number of Times Replaced	Demolition	Lifecycle EE	Lifecycle EG
		GJ	t-CO_2				GJ	t-CO_2
Building								
Structure	Concrete	2,239	462		0		2,239	462
	Steel bars	3,102	299		0		3,102	299
Outer wall finishing	Tiles	241	15		1		481	31
	Metal window frames	469	38		2		1,406	114
	Insulation	34	2		2		101	7
	Fluorocarbon		0		2			0
Internal finishing		1,769	142		4		8,844	712
Other work for building		992	79		5		5,953	472
Subtotal		8,845	1,038				22,125	2,097
Electric	Transformers	7	1		2		22	2
	Switching boards	79	6		4		393	31
	Lighting	48	3		9		477	35
	Other work for electric	441	35		4		2,205	175
Subtotal		575	45				3,097	242
HVAC	Chillers	198	15		4		992	76
	Air conditioners	260	20		4		1,302	100
	Fluorocarbon		54	2%	4	70%		261
	Other work for HVAC	657	52		4		3,286	260
Subtotal		1,116	142				5,580	698
Plumbing	Sanitary ware	71	5		2		212	14
	Other work for plumbing	256	20		4		1,281	101
Subtotal		327	25				1,493	115
Lifts		181	15		4		905	74
Site work	Temporary work, electricity bill	1,040	80				1,040	80
Total		12,083	1,344				34,240	3,305
per GFA	/m^2	5.008	0.557				14.190	1.370

Comparison with the simple calculation method

Table 4.14 compares the simple calculation method provided in Table 4.12 and the result of the detailed calculation. Utilizing this simple calculation method, roughly 95% of the entire building has been counted, which would allow calculation of the EEG by identifying quantities in a relatively simple manner.

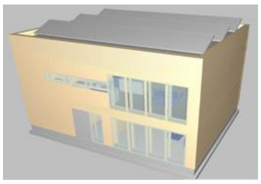
Table 4.14 Results of simple calculation and detailed calculation (Source: Subtask 3 report)

Part	Simple Calculation		Detailed Calculation	
	MJ	kg-CO_2	MJ	kg-CO_2
Total	12,177,252	1,299,455	12,568,761	1,367,120
	97%	95%	100%	100%

5. Measures to reduce EE and EG

5.1 EE and EG of case study buildings

The Annex 57 participants were sent an invitation by email to submit case studies. The studies are based on detailed reports or academic dissertations. Around 80 case studies from 11 countries were collected through this method from across the countries represented within Annex 57. Figure 5.1, Table 5.1 show the summary of case study buildings. An analysis of the case studies from a number of different perspectives is summarized in the following sub-sections. The full analysis of the case studies is found in the IEA EBC ST4 Project report and the full collection of case studies is available in the separate IEA EBC Annex 57, ST4 Case study collection report. All examples of case studies given below refer to a country-number-code that has been given to all analysed case studies in the Annex 57.



Reference period (years)	60
EG (kg-CO2/m2 year)	7.2
EE (kWh/m2GFA/year)	-

The study showed that the emissions from building materials contributed 44% to total emissions. The photovoltaic panels (32%), the concrete (13%) and the EPS insulation (12%) were the building parts that contribute the most.

Reference period (years)	50	100
EG (kg-CO2/m2 year)	22	12
EE (MJ/m2GFA/year)	240	125

30% stronger structure against quake
Thicker covering of concrete surface

(2) Long life and low carbon office (JP)

Reference period (years)	50	100
EG (kg-CO2/m2 year)	7.9	4.8
EE (kWh/m2GFA/year)	89	60

Evaluation of the different building materials showed that for EG, concrete contributed with 42%, steel with 37% and aluminum with 8%.

(3) Novo Nordic HQ, new office building (DK)

Reference period (years)	30
EG (kg-CO2/m2 year)	16.8
EE (kWh/m2GFA/year)	-

Evaluation of the different building materials showe that for EG, concrete contributed with 72.3% and cement(brick) with 8.6%.

(4) Multi-family building (KR)

Reference period (years)	60	
EG (kg-CO2)	-	-
EE (kWh/m2GFA/year)	-	-

The case showed that reuse of materials did not reduce the total env. impact. Although a big part of the structure is from reused materials, the reduction of env. impact in the product stage is not very significant.

(5) Reused versus new materials (CZ)

Reference period (years)	50	100
EG (kg-CO2/m2 year)	8.7	5.1
EE (kWh/m2GFA/year)	80	40

For EG, concrete contributed with more than 50%. A 15% reduction in EG was potentially possible by changing external walls to wood.

(6) New multifamily building (SE)

Figure 5.1 Examples of case study buildings (Source: Subtask 4 Case study collection report)

Table 5.1 Matrix of Case studies part1 (Source: Subtask 4 Case study collection report)

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		
AT1	baubook eco2soft	100	x	x	x						x							New	Office
AT2	baubook eco2soft	100	x	x	x						x							New	Res.
AT3	baubook eco2soft	100	x	x	x						x							New	Office
AT4	EcoBat	60	x	x	x						x		x		x	x		Refurb.	Res.
AT5	Baubook eco2soft	100	x	x	x						x							New	Res.
AT6	Ökobau 2009	50	x	x	x						x				x	x		New	Office
AT7	EcoInvent 2.2	100	x	x	x						x				x	x		New	Res.
CH1	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	School
CH2	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	School
CH3	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	School
CH4	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	School
CH5	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	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	Refurb.	Res.
CH9	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	Res.
CH10	EcoInvent 2.2	60	x	x	x						x				x	x	x	New	Res.
CH11	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	Res.
CH12	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	Res.
CH13	EcoInvent 2.2	60	x	x	x						x				x	x	x	Refurb.	Res.
CH14	EcoInvent 2.2	60	x	x	x						x			x		x		New	Res.
CH15	EcoInvent 2.2	60	x	x	x						x			x		x		New	Res.
CZ1	Envimat	60	x	x	x													New	Res.
CZ2	Ecoinvent 2.2	100	x	x	x	x	x						x	x	x	x		-	Material
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	Res.
DE4	Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK1	PE int	50	x	x	x						x				x	x	x	New	Office
DK2	PE int	50	x	x	x													New	Res.
DK3a	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Res.
DK3b	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Res.
DK3c	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Res.
DK3d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Res.
DK3e	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Res.
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

Table 5.1 Matrix of Case studies part2
(Source: Subtask 4 Case study collection report)

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		
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	Res.
IT2	EcoInvent	50	x	x	x				x		x		x	x	x	x	x	Refurb.	Res.
IT3	EcoInvent	70	x	x	x	x	x		x			x	x	x			x	New	Res.
IT4	(Not specified)	-	x	x	x	x												-	Material
JP1	IO table Japan	90	x	x	x	x	x		x		x							New	Res.
JP2	(Not specified)	-	x	x	x													New	Res.
JP3	Various	60	x	x	x	x	x				x	x	x	x	x	x		New	Res.
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				Refurb.	Office
JP7b	IO table Japan	-	x	x	x	x	x				x	x	x	x				New	Office
KR1	KOR LCI	30	x	x	x	x					x				x	x		New	Res.
KR2	KOR LCI	30	x	x	x						x				x	x		New	Res.
KR3	KOR LCI	50	x	x	x	x	x									x		New	Office
KR4	KOR LCI	30	x	x	x						x				x	x		New	Res.
N01	EcoInvent	60	x	x	x						x							New	Res.
NO2	EcoInvent	60	x	x	x						x							New	Office
NO4	EPD	60	x	x	x	x												New	Res.
NO8	EcoInvent	60	x	x	x						x							Refurb.	Office
NO9	EcoInvent	60	x	x	x						x							New	Res.
SE1	Swedish IO data	1	x	x	x	x	x		x	x	x	x	x					-	Sector
SE2a	EcoInvent, BECE	50	x	x	x													New	Res.
SE2b	EcoInvent, BECE	50	x	x	x													New	Res.
SE3	EcoInvent	50	x	x	x													New	Res.
SE4	EcoInvent	50	x	x	x													New	Res.
SE4	EcoInvent	50	x	x	x													New	Res.
SE5	EcoInvent	50	x	x	x													New	Office
SE6	EcoInvent, KBOB	1									x							Refurb.	Office
SE7	EcoInvent, KBOB, ICE	50	x	x	x	x	x			x		x	x	x	x	x		New	Res.
UK2	BATH ICE, ECEB	N/A	x	x	x	x	x							x				Refurb.	Res.
UK3	(Not specified)	N/A					x											New	Res.
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	Res.
UK7	Bath ICE	60	x	x	x	x	x		x	x			x	x	x	x	x	New	Sports
UK9	data	-	x	x	x	x	x						x	x	x	x	x	New	Res.
UK12	guide to	60	x	x	x	x	x		x	x	x	x	x	x	x	x		Refurb.	Res.

5.2 Impact of methodology on numerical results

The uniqueness of constructed buildings makes direct comparisons of LCA results difficult. In Figure 5.2, cradle-to-gate EC results from a selection of the Annex 57 case studies are shown which represents the wide diversity of calculated results. 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 a 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 5.2 is kg CO_{2eq}/m^2. 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.

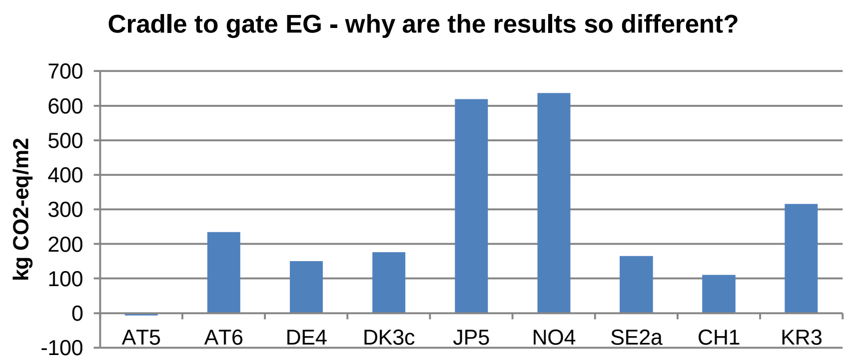


Figure 5.2 Embodied GHG emissions from the cradle to gate stage of different Annex 57 case studies (Source: Subtask 4 report)

Consequently, analysis of the impact of calculation methods and system boundaries applied in the Annex 57 building LCA case studies was an important part of the work of ST4. The analyses made considered the impact of different methodological choices of system set-up on the case study results.

Nine key factors for the wide variation in results from the case studies collected by ST4 were identified, summarized below. For two of these factors, examples are given using Annex 57 case studies to illustrate methodological implications.

1) The purpose of the study
2) The reference study period for the building
3) The chronological system boundaries – for example in some studies the construction stage, and in others even the transport of workers, is included
4) The assumed future scenarios used to determine factors such as service life of materials, and end-of-life treatments. An example is provided in Figure 5.3.
5) The level of completeness of data – whether based on drawings, BIM, or as-built information.
6) The material system boundaries/ the completeness of the inventory – for example, some case studies include mechanical and electrical services and sanitary ware.
7) The LCA approach used - whether process or input-output-based.
8) The source of material data, and the assumptions made within that data. An example is provided in Figure 5.4.
9) The choice of units - for example kg CO_{2eq} per gross internal floor area (GFA) or net internal floor area (NFA), or per year

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

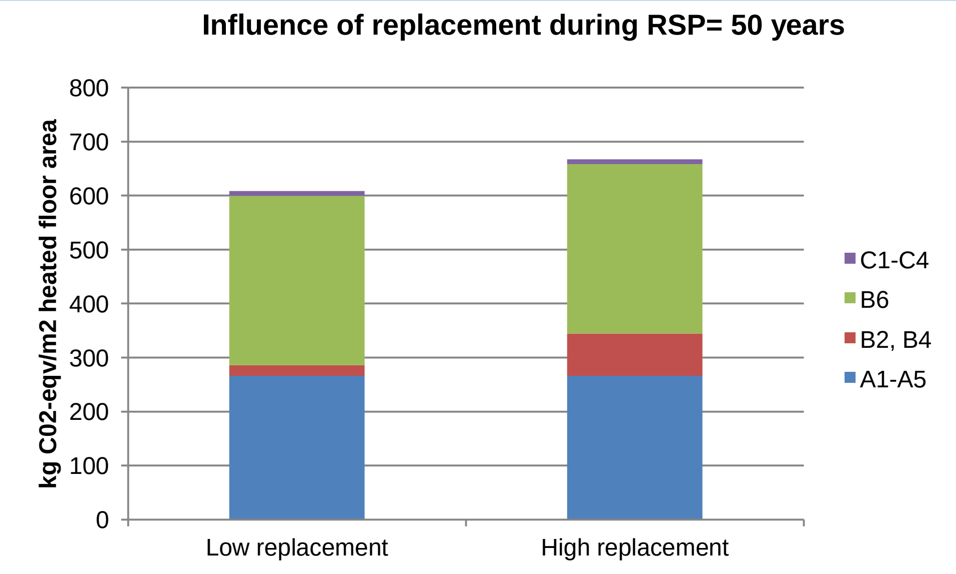


Figure 5.3 Influence of replacement (Source: Subtask 4 report)

Based on data for lowest and highest replacement and maintenance cycles from the literature and manufacturers, a sensitivity analysis is performed regarding the influence of used scenarios for module B4. 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 induce in this example nearly a four-doubled increase in emissions, from 20 kg CO_{2eq}/m2 heated floor area to 79 kg CO_{2eq}/ 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 on. Modules B2, B4 in the figure represent both external replacement and 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.

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 the figure below. The total EC 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.

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.

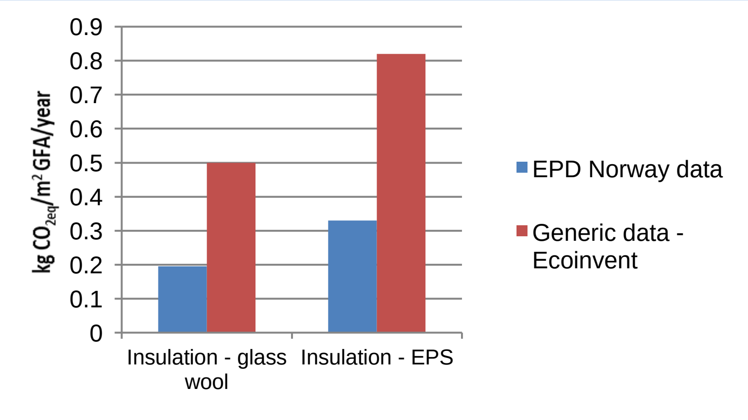


Figure 5.4 Comparison of the use of generic data vs. product specific national data (Source: Subtask 4 report)

However from the analyses presented, it is not possible to say which factor might cause the largest influence on EEG results, as the case studies may be simultaneously influenced by multiple different aspects. It is important to note that the first item in the list above, purpose of the study, is to determine many of the other items. Since the case study compilation in Annex 57 builds on case studies covering a wide range of study purposes, it is fully correct that they should apply different methodological choices. That is, the aim with the case study compilation has not been to compare calculated numbers. However, the analysis done within ST4 regarding methodological implications also clearly display the importance of 1) standardizing method choices for particular purposes, such as declaration, and 2) the need for increased transparency of methodological choices in similar case studies.

5.3 Relative EE and EG due to different life cycle stages and different components

The EEG results presented in Figure 5.2 in section 5.2 illustrate how the uniqueness of not just each building but also of the unique set-up for each study is reflected in the numbers. However, while a wide variation in methodological choices is demonstrated in the Annex 57 case studies, within similar studies it is possible to analyze the relative contributions to EEG from different life cycle stages, building elements, different materials and different processes.

Five general trends were identified (please note that all alpha-numeric definitions are based on the European standard EN 15978):

(1) EEG of different life cycle stages

The production stage (A1-A3) has the highest impact on the whole life EEG (EEG defined as the sum of A1-3, A4-5, B1-5, C1-4) for new buildings, although it may be less than 50% of the total. Figure 5.5 is illustrating this trend for EG by using a number of Annex 57 case studies.

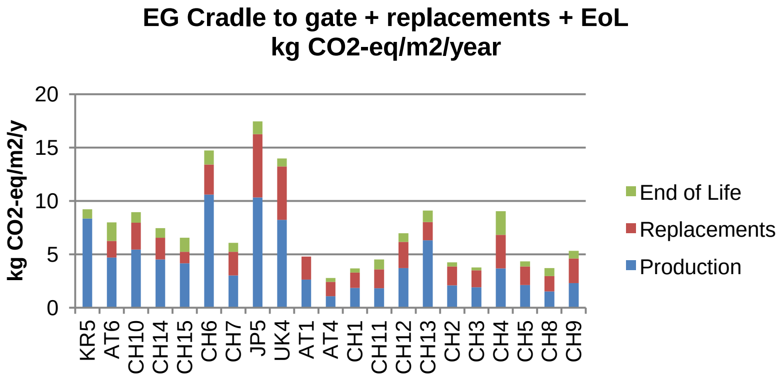


Figure 5.5 Cradle to gate + replacements + EOL EG from available Annex 57 case studies (Source: Subtask 4 report)

(2) EEG for refurbishment cases

For refurbishment cases, the replacement stage (B4) contributes almost the same as the production stage, although this is largely dependent on the product service life. Figure 5.6 is illustrating this trend for EG with the help of Annex 57 case studies. Orange bars indicate case studies where reported results is a sum of production and replacement impacts.

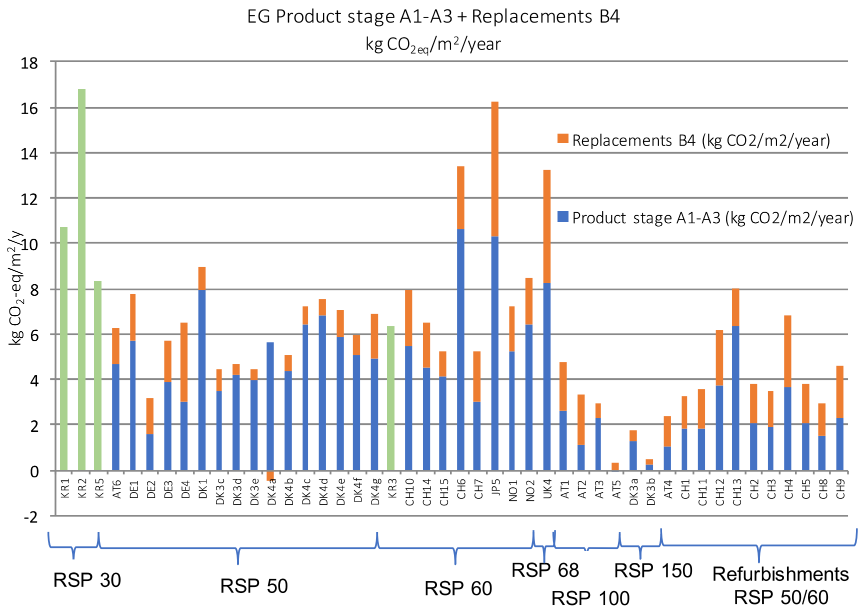


Figure 5.6 Cradle-to-gate + replacement EG from Annex 57 case studies (Source: Subtask 4 report)

Note that in refurbishments of existing buildings, impacts from the production of materials for the refurbishment actions are 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.

(3) EEG of Mechanical and electrical equipment

Mechanical and electrical equipment installed in the buildings may be responsible for a considerable percentage of the whole life EEG. However, it is noted that this is frequently excluded from assessments. Figure 5.7 displays one Annex 57 case study in which the mechanical and electrical equipment amount to as much as 46% of the whole life EEG.

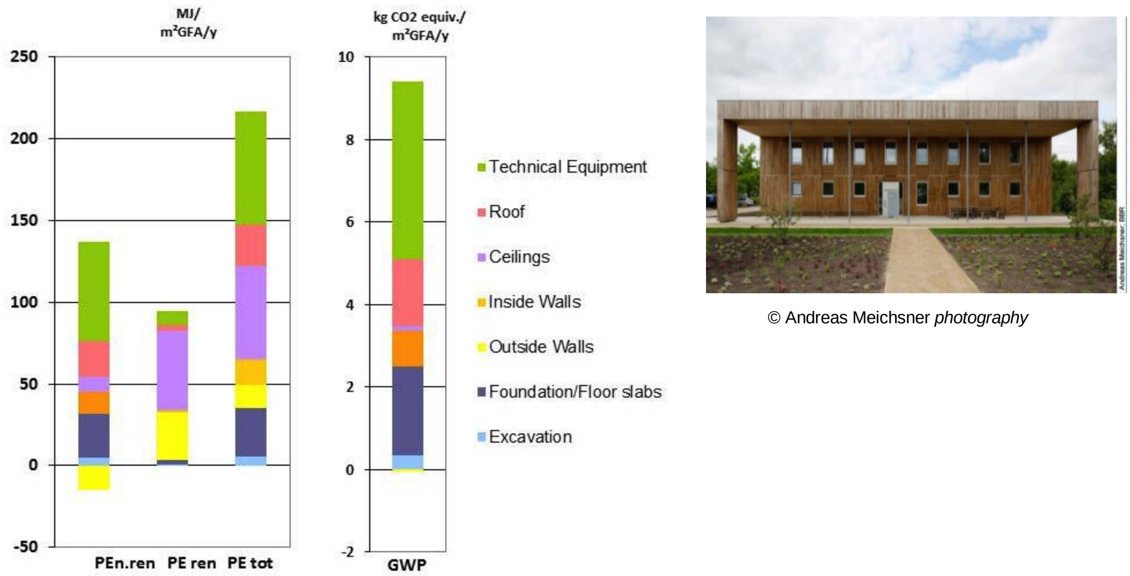


Figure 5.7 Results of the German case study with the code name DE4 (Source: Subtask 4 report)

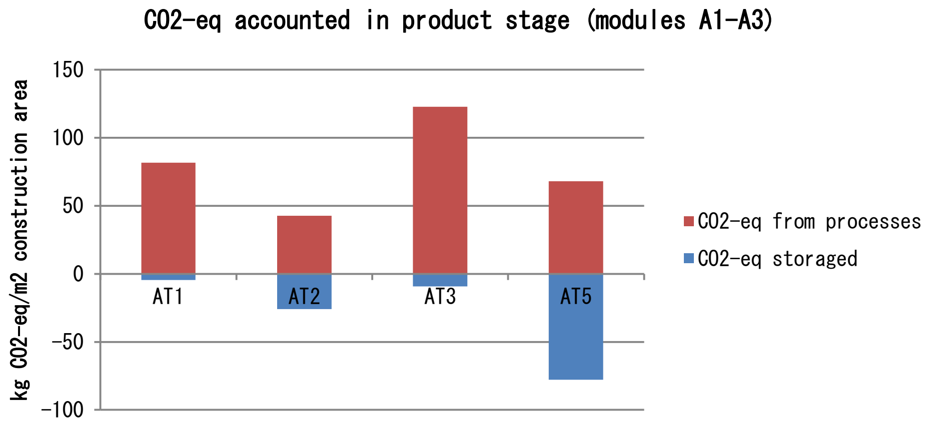
(4) EEG of concrete and metals

Concrete and metals are the material types contributing the most to the EEG of the case study 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 including or excluding the potential recycling benefits post demolition (stage D).

(5) Carbon storage

The results for timber construction are considerably affected by whether or not carbon storage is included (see in Figure 5.8). However either way, where timber is used as an alternative structural material to concrete or steel it is shown to reduce EEG.

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



Bar charts show contributions from processes as well as the temporarily stored CO2 in wooden materials

Figure 5.8 Embodied GHG emissions from cradle to gate of Austrian Annex 57 case studies (Source: Subtask 4 report)

5.4 Strategies for the reduction of EE and EG

Design and construction strategies to reduce embodied energy and embodied GHG emissions include three main categories; substitution of materials, reduction of resource use, and reduction of construction and end-of-life stage impacts. Often individual design strategies will address more than one category. The main conclusions from the review are summarized below.

(1) Use of natural materials

The use of natural and bio-based materials is shown to have a high reduction potential, often due to the simple and low-energy production methods. However there is limited data for many traditional natural materials, which has the converse impact of limiting their use where embodied impacts are required to be calculated. There is a clear need for national and international level support to support manufacturers to develop data for these low carbon materials, which are often produced at low cost and in low volumes. Figure 5.9 provides an example on an Annex 57 case study comparing a timber structure with a steel structure for a new school building. The example displays that bio-based materials are not always favourable in all contexts. In this particular example, the timber structure is the best design choice if studying EG, but not if studying EE.

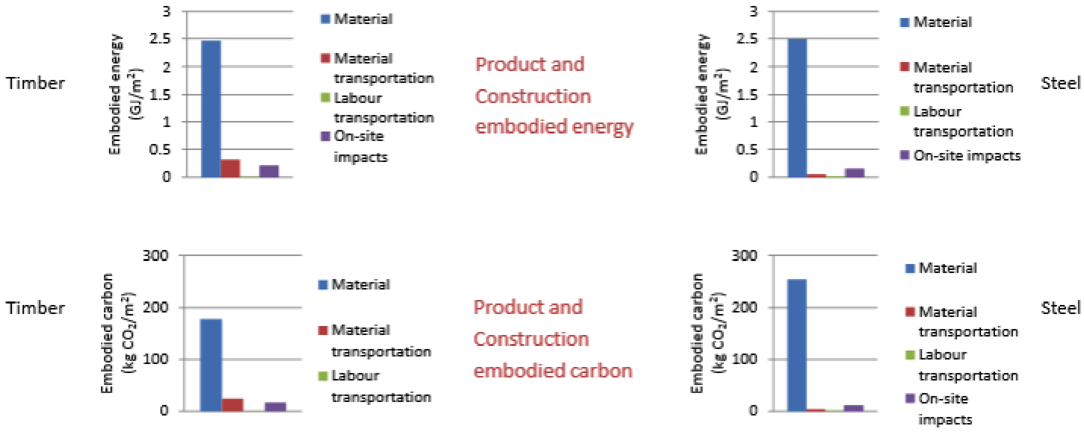


Figure 5.9 Results of the UK case study with the code name UK7 (Source: Subtask 4 report)

It should be noted that the level of EG savings of using natural materials in the analysed case studies is highly dependent on the inclusion of carbon storage or not in the calculations. This fact again illustrates the implications of methodological choice also when studying the potential of various strategies to reduce EEG.

(2) Recycled and reused materials and components:

While this would appear to be self-evident, the effect on EE or EG 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 the recycled material, the capability and accessibility of recycling facilities, and the potential need for additional structures and processes when recycled components are used.

(3) Innovative materials

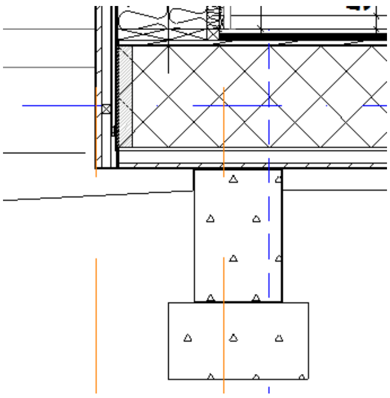
Materials such as wood-concrete composites and high performance concrete have been shown to reduce EEG. However in some cases such innovative materials may cause higher impacts: production methods may still be immature with future efficiency potentials.

(4) Light-weight construction

The impact of light-weight construction is to reduce overall resource use, with considerable potential for reducing EEG. Examples include the use of e.g. strip and hollow foundations, which both reduce the impact of the foundations and put a limit on the weight of the building to be supported. However where above average durability or service loads (for example in earthquake zones) are required this may not be a viable option. Table 5.2 shows results from a Norwegian case study in which the effect of using a light-weight construction was studied. Analyses of NO1 and NO4 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 carbon concrete was used.

Table 5.2 An Annex 57 case study illustrating how EG can be reduced by implementing a light-weight construction. (Source: Subtask 4 report)

CS No.	Building type	Main materials (load bearing structure)	RSP	LC phases	Observations about EE	Observations about EG
NO4	Timber frame, single storey, residential/ demonstration building *(As built)*	**Design Drawing Stage** 1) Timber frame, mineral wool insulation (envelope), concrete in foundation, VIP used with glazing. 2) 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

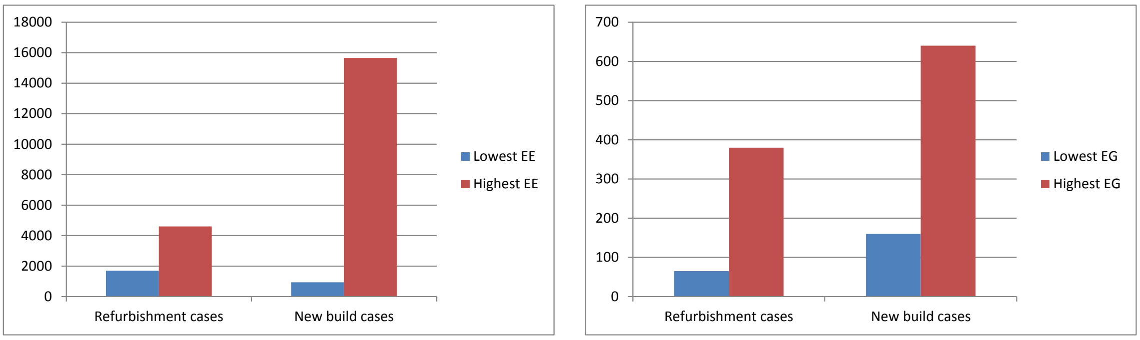


The sketch is from the design stage (courtesy of Bergersen Arkitekter AS), and the photograph (courtesy of Marianne Rose Inman) is from the construction/as-built stage. Note the missing concrete pier foundation and additional insulation.

Figure 5.10 Details for the NO4 concrete foundation (Source: Subtask 4 report)

(5) Reuse of building structures

There are considerable potential EEG savings from reusing building structures rather than demolishing and rebuilding even though large refurbishments may also involve large EEG. Figure 5.11 displays the range in a selection of Annex 57 case studies.



Left diagram displays EE in MJ/m2 and right diagram displays EG in kg CO2e/m2.

Figure 5.11 Range of values for a selection of Annex 57 refurbishment vs. new build case studies (Source: Subtask 4 report)

(6) Design for low end-of-life impact

There is little current information on the impact of design for re-use. However with more of resource efficiency policies, such as the promotion of a circular economy, design strategies to encourage reuse of building components are likely to become more widespread. Predicting future waste and recycling practices remains uncertain, as do issues such as the longevity of the building.

(7) Building form and plan

Several cases show that more compact building forms can reduce EEG. However, compared to material substitution, this strategy is giving lower reduction potentials.

(8) Flexibility and adaptability

Design for adaptability may 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. 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 increase in life cycle impact.

(9) Low maintenance need

There were few cases found where this 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 is required in this area.

(10) Service life extension

Extending the service life of buildings is an obvious way of decreasing total EEG from the built environment. 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. However each building should be assessed for its likely longevity depending on its purpose and on the context within which it is constructed. Table 5.3 provides an example of reduction potentials for design for service life extension.

Table 5.3 Case studies illustrating how EEG of buildings can be reduced by design for service life extension (Source: Subtask 4 report)

CS No.	Building type	Main materials (load bearing structure)	RSP	LC phases	Observations about EE	Observations about EG
JP4	Library building	1st scenario: Reinforced concrete construction with service life of 60 years 2nd scenario: Reinforced concrete construction with service life of 100 years and earthquake resistance	100 years	A1-3	30-35% reduction in second scenario, depending of earthquake resistance strength.	20-30% reduction in second scenario depending of earthquake resistance strength.

(11) Reduction of construction stage impacts

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 a 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).

It is clear from the review that there are still limited numbers of case studies and scientific literature assessing the importance of a number of the potential EEG reduction strategies taken up above, which suggests interesting areas for further research. In addition, several of the strategies are correlated. These correlations can both be positive and negative which supports the recommendation to calculate EEG in the design process to find the best combination of strategies for the individual project.

5.5 Decision making contexts on embodied impact reduction

The above sections have shown a number of ways in which embodied impacts can be reduced from buildings. Each of these is the result of a decision or decisions by one or more stakeholders. This section considers the contexts which support or obstruct those decisions from being made.

Some of these contexts arise from intentional actions taken to reduce embodied impacts, including international, national and regional regulations, and national initiatives (often from industry rather than Government). An overview of the Annex 57 countries showed that there is little currently in the way of specific regulation to reduce EEG from buildings (seeTable 5.4). However a wide number of non-mandatory certification schemes, databases and tools are listed, having been developed across many of the countries. Individual Environmental Product Declarations (EPDs) are also becoming more common, although they are currently difficult to use in analyses due to a lack of conformity. Unintentional effects of climate, culture and economy on EEG were also considered, 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.

Table 5.4 Responses to the Annex 57 Subtask 4 questionnaire (Source: Subtask 4 report)

	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	

The chapter then considered the decisions made for individual construction projects, structuring these as procurement issues, design, and construction, then considering which stakeholders can make a difference. The evidence considered in the chapter suggests that EEG be reduced through decisions taken at all stages in a project's life, although those at procurement and early design stages are paramount. Importantly there are a number of different actor-stakeholders who have both the responsibility and the power to reduce EEG through their decisions.

Some interesting conclusions can be drawn. 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 organizations or groups of construction firms, has also been demonstrated repeatedly and across different countries. Innovative materials and processes can be used to reduce impacts, but these need to be supported at a high level in order to be accessible to small and medium-sized construction projects. Finally tools and databases which are often likely to exclude new materials or contain out-dated or incomparable data, are shown as both useful but also potentially limiting, as are certification schemes.

While not all contextual issues have been covered, it is hoped that the overview provided will help practitioners to understand their own potential to make a difference in the reduction of embodied energy and greenhouse gas emissions 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.

5.6 Concluding remarks

The analyses of the case studies provided in the IEA EBC Annex 57 Subtask 4 Report and the Subtask 4 Case study collection Report have shown the wide range of numerical results emanating from current academic calculations of EEG. The numbers have been analyzed to demonstrate the impacts of the chosen methodology, of the data accuracy, of the boundaries, and of the assumptions made in the calculations; these impacts explain the reasons behind many of the differences in these numbers. Using this knowledge, the case studies were then used to propose specific design strategies which reduce the embodied impacts of buildings, the contexts in which the decisions to measure and reduce EEG of buildings may be taken, and the responsibilities of different stakeholders for reducing embodied impacts under different circumstances.

The use of the case study template was, to our knowledge, a unique approach to gathering diverse data from a wide number of academic participants. Each case study was based on a more extensive publication, including peer-reviewed journal and conference papers. The collection of the case studies, and their careful analysis through four different approaches, has produced an important body of work, as contained within the Subtask 4 Report and the Subtask4 Case study collection Report. This will push forward the understanding of the extent of embodied impacts of buildings, and of the methods by which we can reduce them.

6. Challenges remain and future works

6.1 Summary and outlook of Annex57 results

Various actors in the building and construction industry have recently recognised the growing importance of embodied energy (EE) and embodied greenhouse gas emissions (EG). However, a significant, and still considerably untapped, opportunity to limit these impacts along with the operational impacts of buildings remains. However, the embodied impacts are important and indispensable aspects of the overall performance and sustainability of construction works and thus, their consideration and calculation should become the norm worldwide.

Towards this direction, Annex 57 identified key actor/stakeholder groups influencing embodied impacts along the building supply chain and investigated whether and to what extent specific actions are required. Additionally, Annex 57 investigated how to achieve a stronger integration of embodied impacts into the diverse decision-making processes. As a result, actor-specific guidelines were developed.

Besides that, Annex 57 investigated the transition of the existing experiences of dealing with "embodied energy" to the newest concept of “embodied GHG emissions” and made a clear distinction between the latter and stored carbon. At the end, as a result of this analysis, recommendations for uniform definitions were developed and a basis for the description of system boundaries was provided. For the first time, such an analysis was used as a basis to declare and classify diverse case studies from different countries in an overall system. Finally, the necessity to improve the transparency and quality of data for construction products and assessment results for buildings was identified and analysed.

Operational and embodied impacts work hand in hand, and therefore they should be combined to form an overall approach that would have, among others, consequences for the further development of the EPBD in Europe. The relationships and interdependencies between operational and embodied impacts should be analysed in a future project. Additionally, extending the scope of GHG assessments to include embodied GHG in addition to operational GHG facilitates the determination and assessment of a carbon footprint for the building. Finally, more than ever EEG targets and benchmarks should be defined to assist the design process.

6.2 EEG as standard practice

The ‘danger’ of LCA calculations is that they can be used to produce discrete figures for EEG, which politicians and other decision-makers may then be tempted to take both as accurate and as universally applicable. The more complete explanation given in this report conversely runs the risk of assumptions that the approach is fundamentally flawed, or so inaccurate as to be meaningless. However this report has also demonstrated that as LCA methodology is becoming adopted more frequently, there are relevant conclusions and recommendations that can be drawn.

The availability of transparent data 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 these data is made a global priority.

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. However the potential to significantly reduce the EEG from buildings, through a wide range of different measures, has been clearly demonstrated through the work of the Annex 57.

We recommend that calculations of embodied energy and greenhouse gas emissions are conducted as standard for all buildings, just as in more recent years the operational impacts have been calculated. The development of policy instruments, possibly including regulation, to encourage this should be a priority for all governments.

6.3 Practical measures to reduce EEG

The whole aspects of EEG are illustrated through IEA-EBC Annex57 work, impact of EEG in the world, state of art of existing research relating to EEG, calculation method of EEG and measures to reduce EEG, and so on. EEG is one of the indicators to design and build better building. The results of Annex57 suggest that long life buildings, recycle and natural materials, non-Freon materials and equipment are effective, but the practical measures to reduce EEG are not concluded. It needs further study on development of practical design and construction methods, building materials and equipment relating to reduce EEG for future challenges.

6.4 Technology transfer to developing countries

EEG in Asian countries is considered to be very large and it will further increase. It is expected to decrease elongation of EEG by spreading long-life buildings and reducing usage Freon. Transferring the results of Annex 57 work and technologies relating to EEG reduction into developing countries will contribute to reduce energy consumption and GHG emissions in the world.

6.5 Integrated into Building Assessment Tools

Many assessment methods and tools relating to operating energy and EEG of buildings have been developed and implemented in the world. It is expected to reflect Annex57 results in these methods and tools and improve them into practical ones.

6.6 EEG in Education

It is considered that the whole aspects of EEG are not fully recognized and grasped. It needs to spread the results of Annex 57 work to utilize building design and construction, and to accommodate society's demands of wholesome buildings. EG associated with buildings occupies 20% of total GHG emissions in the world, therefore it is important to cover EEG of building in education as well as industrial products and agricultural products.

6.7 Combining impacts of construction and operation of buildings

After focusing on the construction phase, building renovation as well as embodied impacts (energy and GHG emissions) it is time to merge the knowledge gained so far. Focusing on only one of the aspects may lead to severe sub-optimisation. Too much effort on reducing the energy demand for building constructions may lead to an inefficient use of energy during the use phase of a building and too much focus on reducing the energy demand during operation may lead to too much embodied energy.

The objectives of potential future Annex are the following

- Establish a common methodology guideline to assess the life cycle based primary energy demand, greenhouse gas emissions and environmental impacts caused by the energy use of buildings
- Apply this methodology on a sample set of building case studies to derive benchmarks
- Derive regionally differentiated guidelines and tools (eventually linked to BIM) for architects and planners to design buildings with a minimum life cycle based energy, carbon and environmental footprint
- Develop national/regional databases with regionally differentiated life cycle assessment data tailored to the construction sector, covering material production, building technology manufacture, energy supply, transport services and waste management services

The scope of a potential future Annex may cover dwellings (single and multiple family housings), office buildings and possibly school buildings, both new and retrofit buildings. The life cycle should cover the stages product (production of construction materials including resource extraction), construction process (erection of the building), use (operational energy and water use, maintenance, repair and replacement), as well as end of life (de-construction, waste processing and disposal). The indicators addressed may comprise primary energy demand (non-renewable and renewable), greenhouse gas emissions as well as environmental impacts caused by energy use.

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