EBC

Energy in Buildings and
Communities Programme

International Energy Agency

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

Subtask 3: Evaluation Methods of Embodied Energy and Embodied GHG Emissions in Building and Construction

November 2016

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

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Subtask 3: Evaluation Methods of Embodied Energy and Embodied GHG Emissions in Building and Construction

November 2016

Edited by
Seongwon Seo and Greg Foliente
CSIRO, Australia

Key contributors
Keizo Yokoyama[1], Rolf Frischknecht[2], Manish Dixit[3]
[1] Kogakuin University, Japan
[2] treeze Ltd., Switzerland
[3] Texas A&M University, USA

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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 (*)
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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 (*)

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Executive Summary

This report is part of a suite of publications of IEA Annex 57, which deals with the Evaluation of Embodied Energy (EE) and Embodied GHG emissions (EG) for Building Construction. The purpose of Sub-Task 3, which produced this report, is to present the different calculation methods, and a common and transparent reporting format for the evaluation of EE and EG (EEG) in building and building materials/elements.

For the “data supplier”, who is considered herein as the type of stakeholder who provides or supplies the embodied impact data (in practice, this means the product manufacturer, the Life Cycle Assessment [LCA] expert or consultant, and the database and/or tool developer), this report identifies the issues that need to be addressed in the calculations for a consistent set of output information, regardless of methodology. For the “data user”, taken as the stakeholders who seek and use the embodied impact data to make a business, technical or policy decision (such as the building client/procurer, designer/architect/engineer, and policy maker), the eventual intent is to ensure the appropriate interpretation and application of embodied impacts data, and thus, facilitate improved stakeholder and context-based decision-making. Because of the diverse range of stakeholder or actor perspectives and interests, the specific reason(s) or purpose(s) for evaluation determines the selection of appropriate methods of embodied impacts calculation.

Starting from the definitions and fundamental concepts of EEG in Sub-Task 1 and based on existing international standards and guidelines, the detailed elements, basis and procedure for different calculation methods for EEG for building and building materials are presented. These are:

- Process-based LCA
- Input-Output analysis and
- Hybrid analysis.

It is clear in the comparison of these methods that each one has pros and cons. Thus, the main consideration in selecting which method and resulting data to use is the appropriateness of the selected method for the purpose and context of a decision making task. This is the reason for the introductory discussions on the different types of stakeholder or actor roles, perspectives and interests in this report.

The primary database of EEG is important and significantly influences the quantification of total EE and EG of buildings and construction works. This report provides the main steps to develop the database for EEG for building materials based on each of the analysis (process based on LCI data and IO data). Hybrid analysis is based on the combination of both analysis, thus it is not described here. Whatever method we use for quantification of EEG, the database should cohere at least six minimum requirements; materiality, consistency, transparency, timeless, reliability and quality control.

An example building is shown to illustrate quantification of EEG in the design stage. The example shows large differences between the initial embodied and total embodied impacts (energy and GHG emissions), which are mostly coming from building envelope and HVAC systems. This suggests that efficient selection of building materials in the design stage is quite important as is the inclusion of HVAC systems which contribute greatly to embodied impacts due to coolant leakage.

Four detailed bills of quantity data (from Australia, Canada, Norway and UK) are used to identify and compare the key building materials which influence the total embodied impacts for detached houses. The results show that substructure and walls are dominant elements for building construction, but building material influences vary slightly depending on the geographical area. For the substructure in this example, concrete appears to be the most dominant of building construction materials, accounting for more than 80% of total input mass. Brick is the second most dominant material in UK accounting for more than 40% of total input mass. However, there is no single material pattern for wall elements.

Building service life is one of the “hot issues” affecting recurring embodied impacts. Depending on the service life, the material consumption for the building maintenance and replacement could vary greatly. Also EG from the non-fossil fuel based materials are discussed. Insulation material, which may use Freon gases as a blowing agent, has a significant impact on the total EG of buildings. Fluorocarbon leakage also had a high contribution of total GHG emissions. This report also discusses other important issues that may influence embodied impacts of buildings such as recycled/reused materials, new emerging materials, imported materials/products, transportation, on-site emissions and waste management.

It is not easy to compare EEG between different countries, due to many limitations including data availability and comparability, time constraints, etc. Using the World IO table, this report illustrates how some of these limitations can be addressed in calculating the EEG of building construction and civil engineering work in OECD countries.

Future technical research and development needs in practice towards improved practical guidelines for all stakeholders are identified. An extensive set of references and appendix materials are provided for interested readers.

1. Introduction

1.1 Background

Based on IPCC (2007) estimates, about 40% of the global energy consumption and more than 30% of greenhouse gas (GHG) emissions from human and economic activities may be attributed to the operation of buildings and the construction industry (Langston and Langston, 2008; Lippiatt, 1999; Dixit et al., 2012a, IPCC, 2007; UNEP SBCI, 2009). The energy consumed in building operations to keep the building occupants productive and do so in relative comfort compared to external natural climate conditions vary by country because of different climates and energy use patterns. For example, its contribution to national energy consumption is about 38% in the US (US DOE, 2011), 23% in Australia (AIA, 2008) and 27% in the UK (DEFRA, 2006). But these oft-cited figures do not include the energy used in the manufacture and transport of products that constitute the whole building nor the construction processes themselves.

The total building energy consumption and corresponding GHG emissions can be divided into several parts: embodied, operation and demolition. A few countries, such as Switzerland, even include a portion of the transport energy consumed by the building's occupants to and from the building's location as well, and attribute this to the building under analysis (SIA 2040, 2011). As significant efforts to increase the energy efficiency in building operations continue – e.g., 18% improvements in building energy efficiency in Canada between 1990 and 2005 (NRC, 2008) – the proportion of the other parts, particularly the EEG increase. For example, over a 50-year life cycle of a low energy building in Sweden, Thormark (2002) demonstrated that the EE could be up to 45% of the total energy. Sartori and Hestnes (2007) showed that the EE contribution could range from 2% to 38% for conventional buildings, and from 9 to 46% for low energy buildings. Yohanis and Norton (2002) evaluated the variation of EE over the life span change (25 years to 100 years) for low-rise office building in UK, and showed that although the longer life span has greater operational energy, due to increased energy efficiency and recurring EE, the total EE contributes an increasingly higher proportion (from 20% for a 25-year to 42% for a 100-year life span of the building). This is similar to Crawford's (2011) estimate, where the EE contributes up to 45% of the total energy demand of a Melbourne building over a 50-year life span. The trend towards net-zero energy and net-zero emissions for new buildings (e.g. Directive 2010/31/EU) further highlights the increasing importance of embodied impacts.

The increasing industry interest in accounting for the embodied impacts (energy and GHG) in building and building products from various stakeholders is reviewed in the Annex 57 Sub Task 1 (ST1) Report (Luetzkendorf and Balouktsi 2015). The methods of calculating EEG 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 specific challenges include:

Different quantification methodology (Optis and Wild, 2010; Dixit et al., 2010; Bilec et al., 2006; Crawford, 2008; Crawford and Treloar, 2004; Praseeda et al., 2015; Minx et al., 2007)

Unclear or different system boundary definition (Dixit et al., 2013; Suzuki and Oka, 1998; Davies et al., 2014; Matthews et al., 2008; Abanda et al., 2013; Scheuer et al., 2003; Udo De Haes and Heijungs, 2007)

Lack of accurate or quality data (Khasreen et al., 2009, Optis and Wild, 2010; Treloar et al., 2000; Ding and Forsythe, 2013; Davies et al., 2014; Scheuer et al., 2003)

Depending on different system boundary definitions, data sources and methodology, results may vary (sometimes very significantly), and thus influence key decisions by stakeholders. In order for designers and consultants to incorporate the embodied impacts in the building design and procurement process, for example, Lützkendorf et al (2014) have presented key practical guidance (e.g., system boundary, clear definitions, data source documentation, etc.). Many have previously argued the need to develop such guidelines for different stakeholders in the building and construction sector (Balouktsi et al., 2015; 2016; Lützkendorf et al., 2014; Dixit et al., 2013, 2015; UKGBC, 2014).

1.2 Objective

This report presents the different types of data sources and calculation methodologies to evaluate the EEGof construction products, whole buildings, and parts and processes in the building industry sector, based on a common framework and transparent reporting format. The important technical features of each methodology are presented to ensure appropriate interpretation and application of results, and thus, facilitate improved stakeholder and context-based decision-making.

1.3 Overview

The key elements of a generalised embodied impacts evaluation process are illustrated in Figure 1 (from left): dataset preparation and organisation, evaluation calculation methods, output formatting and documentation and application of results for a specific purpose and/or decision-making context.

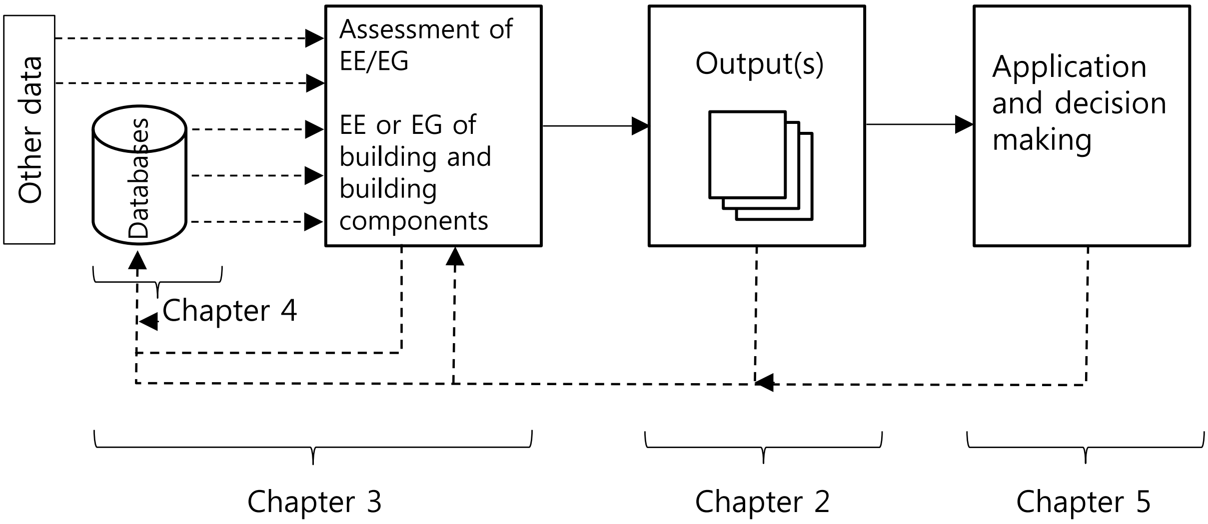


Figure 1 An overview of the key elements of the general evaluation process of embodied impacts in building and building components, with reference to their place (or chapter) in this report.

This report covers all these key elements, and is structured as follows: Chapter 2 presents the basic concepts and definitions of key terms, the similarities, commonalities and differences between EEG; the supporting details needed in reporting embodied impacts data; and the types of stakeholders and actors that are recommended to calculate or use embodied impacts data, considering the diverse range of their decision-making contexts. Chapter 3 presents the detailed elements, basis and procedure for calculating embodied impacts using a process-based approach, an Input-Output approach and a hybrid approach; a summary comparison table of these approaches is also presented. Chapter 4 describes the main steps to establish process based LCA databases and environmentally extended I/O tables, and presents a summary of commonly available embodied impacts databases and evaluation standards or guidelines in various parts of the world. The chapter also identifies specific issues or topics that need to be considered in calculations to provide clarity for both embodied impacts data suppliers and data users, which if ignored may lead to misunderstanding, or worse, inappropriate decision outcomes. Chapter 5 presents a range of practical and detailed calculation examples to illustrate the application of the methodologies in greater detail and for specified contexts; and identifies the required technical research, and developments in practice towards improved practical guidelines for all stakeholders. Then, a summary of key concepts and recommendations is presented in Chapter 6. Finally, an extensive set of references and appendix materials is provided for interested readers.

2. Framework and reporting format

2.1 Basic Concepts and Definitions

A comprehensive discussion of the historical development of concepts relating to EEG in building and construction are provided in the Annex 57 ST1 Report (Luetzkendorf and Balouktsi 2015). Complementary information is presented below, culminating in the harmonised set of definitions recommended therein.

EE of a building 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, EE also includes 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). Thus, EE can be divided into three parts:

- initial embodied (including construction stage),
- recurring embodied and
- demolition.

The initial EE includes energy used in material manufacturing, transportation and construction (Davies et al., 2014; Yohanis and Norton, 2002). Often, this term is used only for the manufacturing phase finishing at the factory gate, so this needs to be clearly stated each time. The recurring EE is the energy consumption related to material or components replacement and maintenance during a building's life (Yohanis and Norton, 2002; Treloar et al., 2000; Crawford, 2004). Dixit et al. (2012a) discussed the range of parameters causing challenges in embodied data analysis. In their study, EE is termed as energy consumption during the whole processes of building material production, on-site delivery, construction, maintenance, renovation and final demolition. But many studies are not clear whether EE includes energy used in maintenance and renovation or not. The demolition EE is associated with the disassembly and demolition of the building. The total EE over the life cycle of a building is the sum of all three (see also BOX 1 and Table 2).

Thus, as recommended in the ST1 Report (Lützkendorf and Balouktsi 2014) two different EE definitions (EE1 and EE2) are proposed (summarised in BOX 1). EE1 takes into account the energy supplied from "Primary energy non-renewable (PEnr) resources, while EE2 accounts for "Primary energy total" (PEt), which sums up non-renewable and renewable primary energy consumption.

EG is the total amount of greenhouse gases that are emitted from the mining and processing of natural resources to manufacturing, transport and product delivery, including formation of buildings, their refurbishment, and subsequent maintenance and demolition, and waste treatment of the building materials (UKWIR, 2008; RICS 2011), expressed in kg carbon dioxide equivalents (kg-CO_{2eq}). Because different greenhouse gases have different contribution intensities to climate change impacts, measured in global warming potentials (GWP) as shown in Table 1, their effects are quantified relative to the GWP of 1kg of CO_2 (thus, the use of the unit kilograms of carbon dioxide equivalent), usually considering a 100-year timeframe (or some other specified reference period). The measure usually includes GHG emissions from all the chemical reactions *and* the associated energy used in the production of a product. Thus, it is very important to know which GHG in the first column of Table 1 are included in any GHG emissions calculation.

In Annex 57, the recommendation is the set that includes CO_2, methane, nitric oxide, and other global warming gases included in the 5th IPCC report (IPCC, 2013 #4835) in its Chapter 8 (excluding short term climate forcers) and listed in Table 1 (IPCC, 2013), and expressed as "kg of CO_2 equivalent (kg CO_2eq/reference unit/reference study period (RSP))".

Table 1 Global Warming Potential (GWP) relative to CO_2

Common name	Chemical formula	*Lifetime (years)*	*GWP 20 year (CO_2eq)**	*GWP 100 year (CO_2eq)**
Carbon Dioxide	CO_2	See appendix A	1	1
Methane	CH_4	12.4	84	28
Fossil methane	CH_4	12.4	85	30
Nitrous oxide	N_2O	121	264	265
CFCs	CCl_3F etc.	45~1020	5,860~10,900	5,820~13,900
HCFCs	$CHCl_2F$ etc.	26days~17.2	5~5,280	1~1,980
HFCs	CHF_3 etc.	2 days ~200 years	<1~10,800	<1~12,400
Chlorocarbons and hydrochorocarbons	CH_3CCl_3 etc.	65 days ~ 26 years	3~3,480	<1~1,730
Bromocarbons, Halons	CH_3Br etc.	0.8~65	4~7,800	1~6,290
Fluorinated species	NF_3 etc.	1 day~2600 years	<1~13,500	<1~23,500
Halogenated alcohols and esthers	CHF_2OCF_3 etc.	0.6day~119 years	1~15,100	<1~12,400

*IPCC fifth assessment
Source: Myhre et al. (2013)

In building and construction, EG consists of (Jones, 2011; Holtzhausen, 2007; Cole and Kernan, 1996):

- the initial EG (including construction stage),
- the recurring EG, and
- the demolition GHG emissions.

The initial EG, like in the case of EE, is typically taken as the product-based GHG emissions before the construction of the building, including the extraction of raw materials to the manufacturing of products and finishing at the factory gate. As before, this distinction needs to be made each time the term is specified. Generally, the GHG emissions associated with the construction phase of the building, i.e. transport of materials and products and assembly on site. The recurring EG include the emissions associated with the maintenance and replacement of the building or its components. The demolition GHG emissions are those associated with the disassembly and demolition of the building and the disposal (incineration and landfill) of the building materials. The total EG over the life cycle of a building is the sum of all three. (See also BOX 1 and Table 2).

BOX 1 Definition of Embodied Energy (EE) and Embodied GHG Emissions (EG)

Embodied Energy (EE) and embodied GHG emissions (EG) are closely related but *not* the same. The first main reason for this is that different types of energy source and production release different amounts of GHG. The second is that other activities (apart or in addition to those that have direct energy consumption) in the development and delivery of a "product" (which is generically used herein to mean any construction product, constructed asset, facility or building, and even a building portfolio) can contribute to GHG emissions. In other words, GHG calculation includes all GHG emissions not only due to fossil fuel consumption, but also non-fossil fuel related GHG emissions (e.g., chemical reaction for material manufacturing such as calcinations process for cement production, etc.).

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

Embodied Energy 1 (EE1) is the cumulative non-renewable primary energy demand (CED_{nr}) for all processes related to the creation of a product, 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 product.

Embodied Energy 2 (EE2) is the cumulative primary energy (renewable and non-renewable) demand (CED_{nr+r}) for all processes related to the creation of a product, 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 product.

The unit for both definitions is “MJ/reference unit for the reference study period (RSP)”.

Embodied GHG emissions (EG) or embodied carbon: This is the cumulative quantity of greenhouse gases (as specified in the 5th IPCC report), which are emitted during all the processes related to the creation, maintenance and end-of-life of the product (building or building component).

This is calculated and expressed in terms of kg-CO_2 equivalents, i.e. “kg-CO_2eq/reference unit for the reference study period (RSP)”.

The commonalities and differences between EEG in terms of life cycle boundary and source of contributions are summarised in Table 2. The total life cycle embodied impact includes those generated or consumed during product/material manufacturing, construction, use (i.e. recurring) and end-of-life demolition phases.

Table 2 Boundary and emission sources for the EEG of building/building products

			Life cycle boundary	**Source**
EE	Initial	Material	Cradle to gate	Energy requirements to; Extraction of raw material Processing material Assembly of product/components Transport between companies for each steps
		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 Waste processing Disposal including transport
EG	Initial	Material	Cradle to gate	GHG emissions (CO_{2eq}) due to; Energy consumption of initial EE above Chemical reaction (e.g., clinker production of cement) Sequestration of carbon absorbed (e.g., timber)*
		Construction	Site	GHG emissions (CO_{2eq}) due to; Energy consumption of transport-to-site and construction energy Disposal and/or processing of waste
	Recurring		Refurbishment & maintenance	GHG emissions (CO_{2eq}) due to; Recurring EE above Chemical reaction (e.g., clinker production of cement) Sequestration of carbon absorbed (e.g., timber)
	Demolition		End-of-life	GHG emissions (CO_{2eq}) due to; Energy consumption of demolition energy above Burning fossil fuel based materials Burning renewable materials (e.g., timber)**

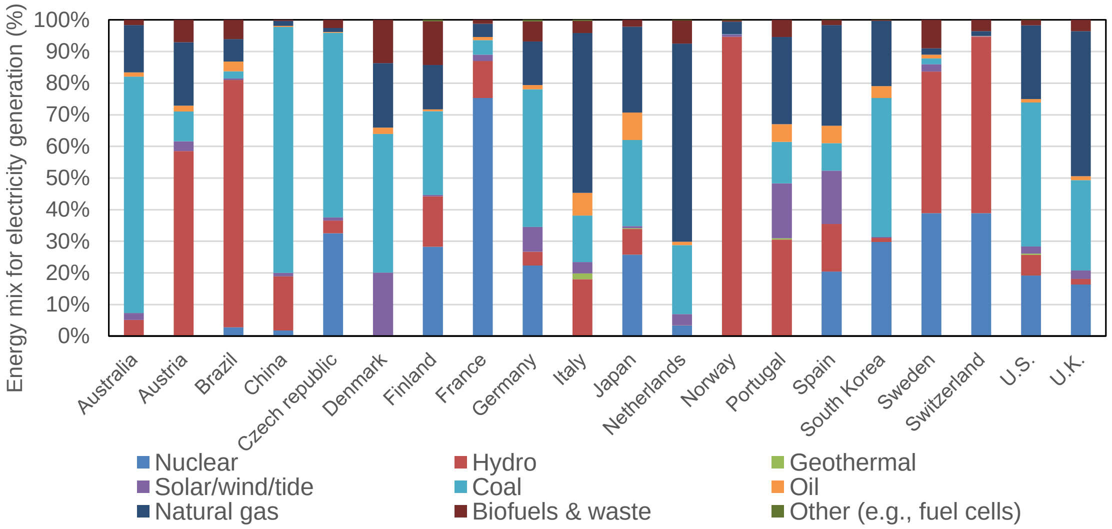
*only if biogenic carbon dioxide emitted is assessed with a GWP = 1kg-CO_{2eq}/kg of biogenic CO_2

The use of the above terms requires the need to be clear about boundary and specific inclusions or exclusions of items from this list. (Some countries, i.e., Switzerland, do not take into account carbon sequestration nor biogenic CO_2 emissions in EG calculation (KBOB et al. 2014)

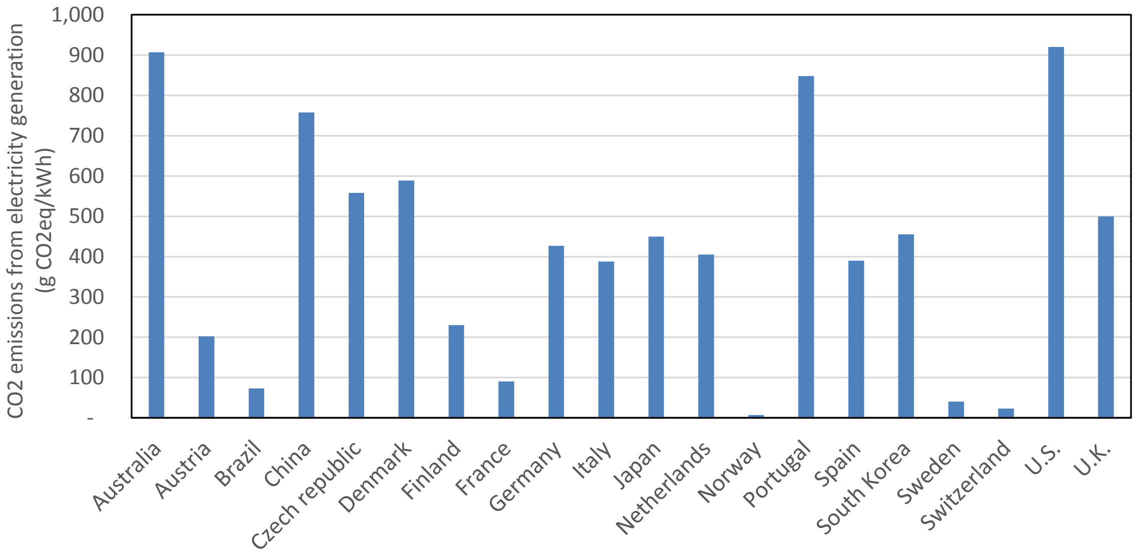
**only if carbon sequestration is assessed with a GWP = -3.67kg-CO_{2eq}/kg of biogenic carbon

The electricity supply mix in different geographical areas and countries has a significant effect on cumulative GHG emissions of buildings. Figure 1 shows the electricity mix in selected countries. Electricity generation in Australia is predominantly based on coal power plants, 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 (Figure 2(a)) means different GHG intensity of electricity (Figure 2 (b)). In Australia 0.891 kg-CO_{2eq} are emitted to generate 1kWh of power. In the UK it is 0.557 kg-CO_{2eq} per kWh (only 63% of Australia's) and in Japan it is 0.365 kg-CO_{2eq} (less than 41% of Australia's).

In calculating EG, this means that it is very important to use the appropriate electricity mix for a given product in a particular country, and to report what reference electricity mix has been used (or assumed).



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



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

Figure 2 Energy mix for power generation and GHG emissions for selected countries

2.2 Reporting format and guideline requirements

2.2.1 Overview

Given the definitions and concepts introduced above, some guidance about the reporting format and documentation of calculated EG is needed further to assist:

- The "data suppliers" – who establish life cycle inventory data and supply them as well as calculated embodied impact data, e.g. database developers, technical consultants and experts who work with manufacturers and industry bodies, and
- The "data users" – who take and apply the calculated embodied impact data to make decisions supporting their context and purpose, e.g. designers and consultants, developers and contractors, owners and investors, public policy makers, etc.

The recommended minimum set of information that will serve this purpose for both data suppliers and data users is illustrated schematically in Figure 3. The "Whats" and "Hows" of EEG should be clear to both groups not just for clarity and improved understanding, but more importantly, to avoid inappropriate use. The basic What-information is described in the recommended definitions in the previous section (BOX 1). The important How-information will include;

- The specific method or approach (M) used for calculating the reported EE and/or EG;
- The product life cycle phases (or system boundary, SB) explicitly included in the reported EE and/or EG; and
- The excluded emissions (X), or the (known) missing embodied impacts in the reported EE and/or EG.

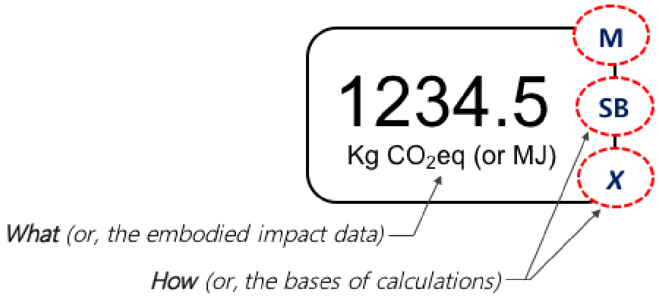


Figure 3 **Illustration of the minimum set of information needed and recommended for embodied impacts data reporting (M: Methodology, SB: System boundary, X: Excluded or "missing" emissions)**

The main reason for this recommended reporting format and documentation requirements is that the embodied impacts' calculation results can vary significantly depending on the calculation methodology, life cycle boundary, and considerations (or not) of excluded or "missing" emissions (Bilec et al. 2006; Crawford 2008; Crawford and Treloar 2004; Ding and Forsythe 2013; Davies et al. 2014; Dixit et al. 2010, 2013; Khasreen et al. 2009; Minx et al. 2007; Optis and Wild 2010; Praseeda et al. 2015; Treloar et al. 2000; Wang and Shen 2012; Webster et al. 2012). The next sections will expand on these effects and present the technical rationale for the above recommendations.

2.2.2 Implications of different methodologies (M)

To calculate the embodied impacts based on the recommended definitions in BOX 1, three methods can be used (Rebitzer et al. 2004):

- Process-based life cycle assessment (LCA)

- Environmentally extended Input-output (IO) analysis, and
- Environmentally extended Hybrid analysis, which combines the two above approaches.

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 quantifying embodied impacts of building s and building components.

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 IO approach is based on national IO 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.

Thus, to aid both data suppliers and data users to better understand and use the resulting calculations properly, the specific methodology (M) used in embodied impacts calculation needs to be clearly identified with the reported embodied impacts data (Figure 3).

2.2.3 Implications of different life cycle or system boundaries (SB)

As will be discussed in greater detail later, each of the calculation approaches presented above requires definition of scope and system boundary in the application of each methodology. In the present section, the focus is the identification of stages in the building production (or product creation) and whole service life that are explicitly included in the calculated/reported embodied impacts of that product or building. Because recurrent embodied impact can be varied depending on the service life of building.

A building’s life cycle includes mainly four phases: “Product” (creation or manufacture), “Construction”, “Use” and “End of life” as shown in Figure 4 (overview) and Figure 5 (detailed components). Over the life cycle of a building, each phase contributes directly or indirectly to EEG, as listed in Table 2. In a building’s life cycle, for example, the EEG in the “Product” phase include those from the extraction of raw materials, including transport, and in product manufacturing (Figure 5). In the “Construction” phase, energy is consumed directly on the site due to the use of machinery. The impact from this stage is also included in the initial embodied impacts of the building. In the use phase, all the sub-categories (B2 to B5) as shown in Figure 5 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”. Use (B1), Operational energy (B6) and operational water use (B7) in Figure 5 are not counted in the embodied impacts calculation. Finally, the energy consumed and GHG emissions to deconstruct, transport, process and/or dispose waste are also included in the embodied impacts in the “End of life” phase. It does not consider embodied impacts of the building beyond the building’s life cycle (Stage D (Benefits and loads beyond the system boundary) in EN15804). But if this is considered, one should be clear about the allocation in the reuse and recycling processes based on ISO 14044 (2006) and the EEG of Stage D shall be kept separate from those quantified for stages A to C.

It is clear that exclusion or inclusion of specific stage(s) in the building life cycle in Figure 5 (e.g. A1 to A5, B2 to B5 and/or C1 to C4) could make a significant difference on the calculated embodied impacts.

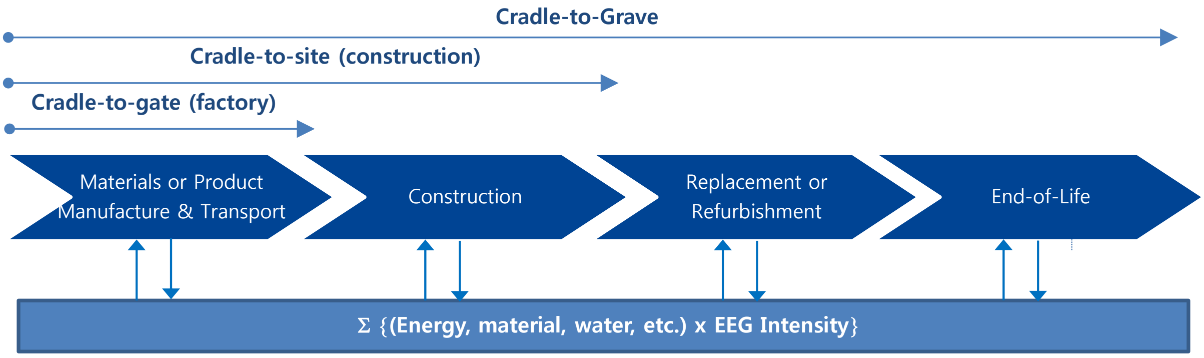


Figure 4 Life cycle of building and EEG classification

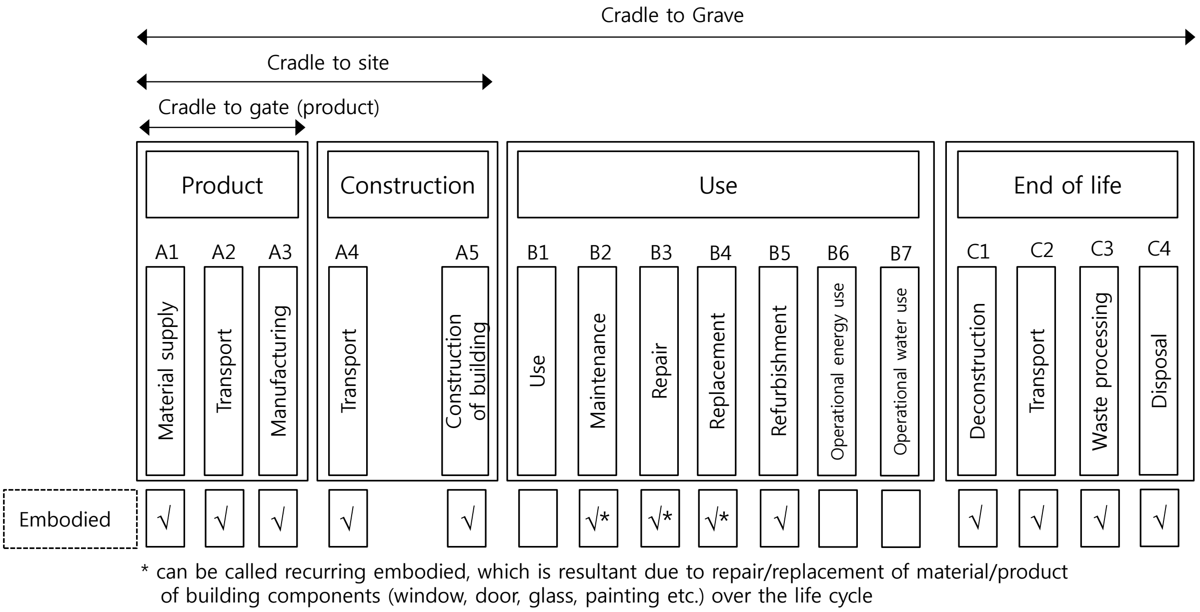


Figure 5 Stages in the life cycle of a building based on EN15978 and link to embodied impacts

Several international standards or methodological guidelines on how to undertake LCA or embodied impacts assessment are available. For example, ISO standards and technical specifications (e.g., ISO 14040s, ISO ST 14047 etc.) and WRI & WBCSD guidance provide how to define and calculate the environmental impacts and carbon footprint of products. The building industry in some parts of the world is already adopting a life cycle approach (e.g. in the form of Environmental Product Declarations [EPD] or LCA results) or including its assessment in building rating tools (e.g., LEED v4, Green Star, SNBS, etc.). However, these are mostly limited only at the product level in Figure 5. There is a number of general standards or guidelines for building at the system level (e.g., CEN TC350, PAS, RICS, BSRIA, SIA, etc., as shown in Table 14).

Although some of them are relatively well documented to guide (e.g., CEN 350, SIA 2032 etc.) but many of them are not very clear on how to deal with the embodied impacts, or which stages of a building's life cycle are included (or not) in reported EE EG for products and building. Data users (policy makers, designers, builders, etc.) are especially confused whether the embodied data covers which life cycle boundary, or what kind of quantification approaches used for the data (described in detail in Chapter 3). Thus, data suppliers should help data users and stakeholders to interpret and use the supplied embodied data more appropriately by clearly specifying the life cycle or system boundary (SB) inclusions (Figure 3).

2.2.4 Implications of excluding or missing emissions (X)

Even when the life cycle boundary inclusions are clearly identified, however, the different missing emissions (or excluded emission as explained in chapter 2.2.1) from the calculations also need to be explicitly identified. This is particularly important beyond the Product phase (A1-A3), for which typically relatively detailed information is available. Specific information such as whether the reported embodied impacts data includes transportation from manufacturing site to construction site, considers waste and treatment from the construction site including its transportation, and/or comprises non-fossil fuel based GHG emissions etc., might bring big difference in results.

Figure 6 illustrates a hypothetical example involving the evaluation of EG of wall insulation of an existing house (240m^2 total floor area). The right-hand side shows a life cycle boundary diagram of insulation material (spray foam polyurethane or SPF). The life cycle stage is classified into A1 to C4 (i.e. including A1 to A3 at cradle to gate, A4 to A5 for GHG emissions from installation of material, B1 to B7 at use phase and C1 to C4 for the end-of-life). In this example, 33m^3 of the SPF insulation material (SPF) is assumed (with 20% extra of insulation material, which send to waste treatment facility). Using process-based Australian EG data (FWPA, 2010) for building materials, EG for the whole house were calculated.

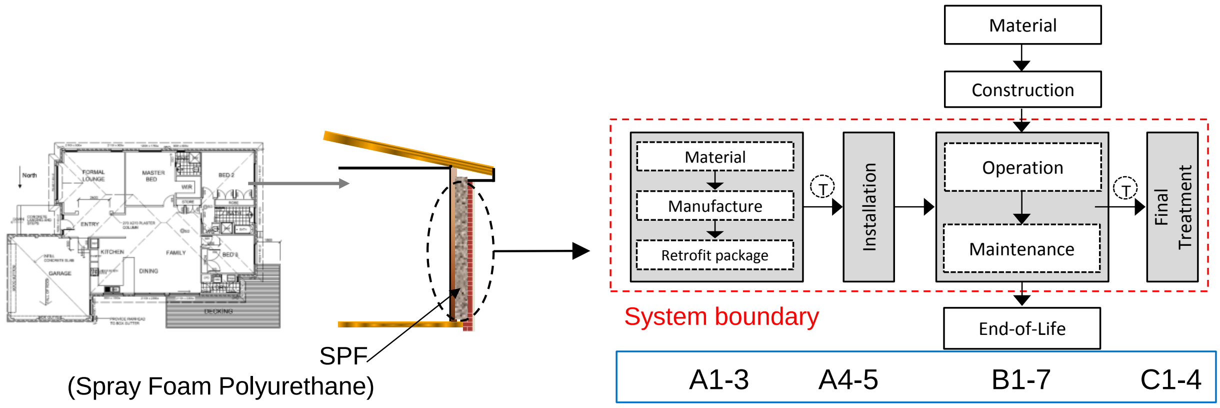


Figure 6 Example of wall insulation with SPF (Spray Foam Polyurethane)

Over the specified (cradle to use) life cycle, 22.1 kg-CO_{2eq}/m^2 of EG was calculated for this example (Figure 6). This is only for the insulation materials for the wall. This example case does not consider other GHG emissions due to:

- Transport of material within the manufacturing site
- 20% of extra of insulation material, which can be lost on site (≈6.15 kg-CO_{2eq}/m^2),
- Transport of waste from the installation site (0.009 kg-CO_{2eq}/m^2),
- Non-fossil fuel based emissions e.g., fluorocarbon emissions from EPS (207.4 kg-CO_{2eq}/m^2) in the use phase, not due to the running of the building, but only from the insulation materials.

When all of the above are considered, the total EG is 235.7 kg-CO_{2eq}/m^2, which is more than 10 times larger than the original EG that did not include the above “missing” emissions.

Table 3 EG (kg-CO_{2eq}/m^2) of insulation material of example house (240m^2)

Life cycle stage	EG	Note
A1 – A3	20.5	
A4 – A5	1.64*	Assumed 8.25% of EG of product*
B1 – B7	0	No emission of use phase
Total (A1~B7)	22.1	

*Assumed 8% of installation based on Buchanan & Honey (1994)

It would be ideal for reported embodied impacts data to always include a comprehensive set of relevant emissions since the difference can be very significant as shown in this simple example. But in any case, an explicit list of included emissions (or deliberately omitted emission) in the supplied calculations should be supplied to aid both data suppliers and data users (Figure 3). These kind of information should be supplied in various options such as tick-list or tick box as shown in Figure 6, text as note, or table with free entries etc. The key thing is to provide transparent information to avoid misinterpretation of the results.

2.3 Stakeholders and decision-making context

The range of uses or applications of embodied impacts data in building and construction are varied and diverse because they differ based on the perspective of a diverse group of stakeholders or actors, who in turn have different roles, decision making contexts and purposes (Balouktsi et al. 2015; 2016). An overview of these roles and contexts for four stakeholder types are given in Table 4 (note that a more detailed classification of stakeholders and their primary roles are given in Balouktsi et al. 2016). Recognition of this wide range of roles, perspectives and applications of EEG data is critical in mapping the embodied impacts calculation process and the choice of appropriate dataset (or calculation method), as discussed in the next chapter. Table 5 shows examples of specific components of embodied impacts during the building life cycle that needs to be considered explicitly by key stakeholders: manufacturers M, designers D and policy makers P. This can be extended to other types of stakeholders identified in Balouktsi et al. (2016).

In reference to the simplified binary classification of stakeholders as “data suppliers” and “data users” in section 2.2.1, only the product manufacturer M in Table 4 and Table 5 is classified as a data supplier (others in this group include LCA experts and consultants, and database and/or tool developers); the others (procurer, designers D and policy makers P) may be classified as data users.

Table 4 A sampling of stakeholders and actors in building and construction, and their diverse decision-making contexts and concerns (from Balouktsi et al. 2015)

Stakeholder/ Actor	Object of assessment (Typical)	Decision making context or situation (Key question or objective)	Type and reason for assessment (Consequences for work flow, methods and data needs)
Designer (Professionals and consultants)	Product Element/component Building (whole)	• Selection and specification of construction products • Optimisation of building elements during the design • Optimisation of building assets during the design stage • Optimisation or balancing life cycle energy/carbon • Selection of scenarios (e.g. end of life) • Documentation of constructed assets at the time of handover	• EEG data for construction products (company specific) are required in order to be linked to the respective product quantities • For the optimisation of building elements and constructed assets during the design, the contribution of the individual construction products (national or regional average for comparison) in terms of EEG must be identifiable and an analysis must be possible. • At the time of handover of the building, EEG must be documented among others.

Product manufacturer (Building, construction and allied industries)	Product	• Selection of raw materials and suppliers (of other materials needed for production) • Selection of energy sources for in-house processes • Selection of technologies for in-house processes • Optimisation of in-house processes • Optimisation of resource efficiency and recycling of the construction products	• EEG data for raw materials and other supplied materials (company specific) are required, as well as PE and GWP data for the energy carriers and services and for transport and waste management services. • For the optimisation of construction products during the product development and the continuous improvement in relation to EEG, the impact of raw materials, energy carriers and in- house processes must be identifiable in the analysis
Procurer (Owners and investors)	Building (Specific product, e.g. new or innovative technology)	• Procurement of constructed assets • Procurement of construction products	• EEG data for constructed assets or construction products is required • Benchmarks (whole system/building level) are required as a basis for assessment and decision-making
Policy maker	National/regional policies National/regional legislation and regulation National economy	• Influence development of industries and sectors • Development of standards and laws (construction regulation) • Development of incentives and funding programmes (to reduce energy & GHG emissions of building)	• An overview across the industries and sectors is required • Environmentally extended IO tables are required.

EEG: Embodied Energy and Embodied GHG emission

Table 5 Consideration of EEG during the building life cycle by key stakeholders (manufacturers M, designers D and policy makers P)

Life cycle		**Consideration**	**Key stakeholder**			**EEG type****		
			M	**D**	**P**	**EEG$_P$**	**EEG$_C$**	**EEG$_B$**
Product	Raw material supply	E&G of intermediate product i for final product k	√			√	√	
	Transport	E&G due to transportation of intermediate product i for final product k	√					
	Manufacturing	E&G due to manufacturing of product on site	√					
	Product	E&G of product (cradle-to-gate, e.g., EPD)	√	√	√			
Construction	Transport to site	E&G due to transportation from factory gate to site						
	Assembly	E&G due to construction site						
Use	Use	GHG emission from building product/element during the life cycle (Use, e.g., CFCs from insulation or plant etc)		√				
	Replacement	E&G of building product due to replacement during life cycle		√	√		√	
	Refurbishment	E&G of building product due to refurbishment during life cycle					√	
End-of-Life	Deconstruction	E&G due to demolition		√				
	Transport	E&G due to transportation of product (to building site)	√	√				
	Waste processing	E&G due to waste processing	√	√				
	Disposal	E&G due to final disposal	√	√				
	Building			√	√			

M: Manufacturer D: Designer, P: Procurer, B: Builder

E&G:Energy and GHG emissions

*Depending on the situation, policymakers may request

**EEG: EE and EG, EEG$_P$: EE and EG of Product, EEG$_C$: EE and EG of Component/element, EEG$_B$: EE and EG of building

3. Calculation methods

3.1 General Overview

The EEG for a product or building project – as defined and introduced in the previous chapter – 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 (i.e. to support a given decision, see Table 4 and Table 5), 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 (original EEG data) are calculated using one or any of the following three methods:

- Process-based life cycle assessment
- Input-output (IO) analysis, and
- Hybrid analysis, which combines the above methods.

Figure 7 provides a generalised illustration of the evaluation process based on stakeholder perspective and decision-making context (left block). The appropriate selection of embodied impact dataset (or calculation for such; right block) depends on the purpose of analysis or the nature and focus of decision making. As an example, for detailed selection of a product or material in a building project, a design team may opt to obtain and use process-based embodied impacts data to compare specific alternative options. Or, a policy maker may obtain and use environmentally extended IO-based embodied impacts data to assess the industry-wide sector impacts of a policy initiative or regulatory scheme. However, in tendering for a project, companies might use more specific process based LCA data. Specific examples, with detailed calculation procedures for selected cases, are provided in Chapter 4.

This chapter presents the technical elements, basis and procedure for calculating embodied impacts using these methods. 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 GHG emission of the system. The last section summarises and compares the key characteristics of each method, including relative advantages and disadvantages. In the next chapter, guidance on preparation of databases based on these methods, and a summary of commonly available embodied impacts databases in selected parts of the world are presented.

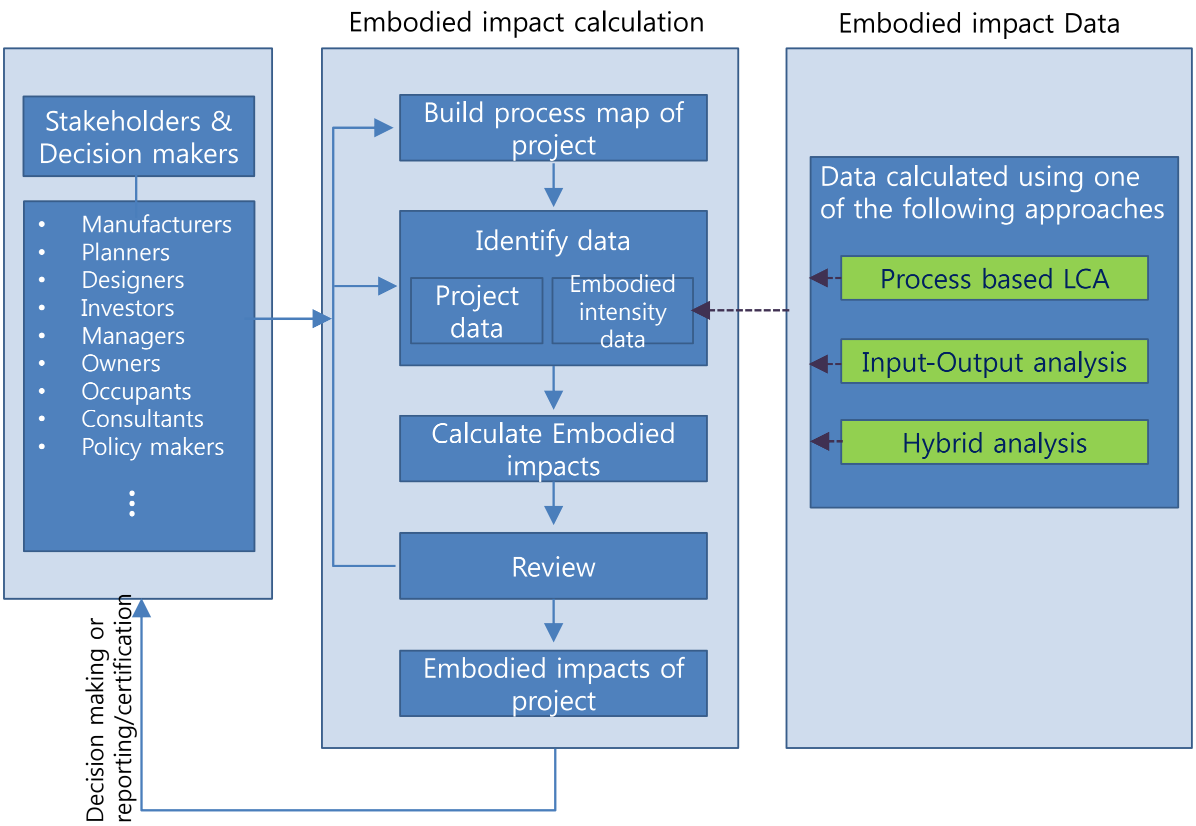


Figure 7 An illustrative diagram of context-based embodied impacts calculation process

3.2 Calculation method of datasets

3.2.1 Process based life cycle assessment

3.2.1.1 Introduction

Process based LCA is a method of collecting data for specific unit processes and linking them into larger processes to model the environmental impacts of product or system over its life cycle. This approach includes the calculation of inputs to the system in terms of raw material and energy consumption, and outputs in terms of emissions to air, water and land. Here, data for all activities in the selected product or system (e.g., whole building) are collected and converted into energy or GHG emissions. This will result in an embodied impact coefficient for the material or component which is often expressed in MJ or kg-CO_{2eq} per unit mass or volume of material/element. This approach can give a reasonably accurate measure of the energy or GHG emissions required to produce a material, component or building assuming all of the energy and GHG emissions are collected. This process-based approach can capture or include specific details at the relevant process level. Primary data, which are collected for key processes during the inventory phase of the LCA, provide robust "hot spot" information that can be used to improve the environmental performance of a building or the building product manufacturing. The approach is widely accepted across various stakeholder groups for energy, GHG and environmental assessment. Currently many international standards of EEG and environmental impacts recommend the process-based life cycle assessment for buildings (e.g., EN 15978, ISO 21930).

3.2.1.2 Calculation method

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 can be used (see UNEP SETAC 2011).

The process based LCA 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 have further refined these criteria. The European EPD standard on construction products, for example, allows one 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 based LCA method applied to buildings requires data on the mass of material and the areas of walls/floors and the like used in the building. This information is known to the planners and architects as they need exactly this information to estimate the initial/preliminary costs and write the call for tenders for the construction companies. With regard to building services such as ventilation systems or electrical systems, generic LCI data are derived from several case studies (e.g., 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 data collection effort required.

Following the general life cycle inventory analysis in ISO 14040 (2006), the material bill of quantities for the targeted building element or building is collected. The data consists of weight, volume, area and thickness etc. These are then converted into the EEG 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 5) and module boundary ("Raw material supply", "Transport", "Manufacturing" within the "Product" stage as shown in Figure 5).

Given the necessary understanding of industry processes, determining data required was an iterative process, as were most of the methodological processes in this module. The knowledge obtained during initial data collection processes let us to refine the data requirements. Data requirements include all input and output information on:

- Energy and Water,
- Waste and Emissions,
- Transport,
- Plant and equipment.

In the "Material" stage, all inputs include quantity data of the required materials, fuels, energy for the manufacturing processes.

In the "Construction" stage, all material requirements and energy and fuel consumption from construction activities (including delivery of equipment, materials and products to the site) are required to quantify energy and GHG emissions.

In the "Use" stage, impacts can be further classified into three parts; use (operation), maintenance and repair/replacement. Environmental impacts due to the use of building components are often considered as operational impact and impacts from the maintenance and repair/replacement are either classified as recurring embodied impacts or subsumed under operational impacts. The input data consist of the material/products consumption data required for maintenance and energy (electricity, fuel, etc.) for all the replacement activities during the use stage of building.

And finally in the “End of life” stage, all inputs are required for disposal and transportation of the targeted products to the disposal site and its processes based on the possible disposal scenarios of building. The input data consist of quantitative materials, energy (electricity, fuel, etc.) for the disposal processes and transportation to the disposal site.

In all the stages above, the main input data are the quantity of materials including transportation distance and types, fuel and energy (electricity, etc.) over the life cycle of product or building.

Once all foreground data have been collected, the analysis can be undertaken using background LCI data (e.g. from a commercial LCI database included in tools such as, Gabi, ecoinvent etc.) and convert them into environmental impacts. EEG are a part of characterized impact in life cycle impact assessment (LCIA). For example, cumulative energy demand (CED) or IPCC GWP (100a) methods can be used for EE (as MJ oil eq. [see Frischknecht et al., 2015 for more detail]) and EG (as kg-CO_{2eq}).

3.2.1.3 Example: Ordinary Portland Concrete product (Australia)

Here we show how to quantify the EEG of an Ordinary Portland Concrete (OPC) as an example using a process-based LCA method. The system boundary is confined to “Cradle-to-gate” (A1 to A3 in Figure 5, from raw materials extraction to the manufacturing plant gate in Melbourne, Australia, prior to delivery to the construction site or regional storage site). LCI data from Australasia LCI database (ver2013) embedded in the SimaPro software are used.

The functional unit of targeted product (OPC) is selected to be 1000 kg of Ordinary Portland Concrete product.

It was not possible to collect all necessary data from manufacturers. Thus, some items in the analysis are assumed as follows:

- Electricity is modelled with the national electricity mix of Australia (Australian average electricity value from ecoinvent data v.2.2).
- The energy consumption for the targeted product (OPC concrete) is assumed to be consumed same amount of energy and fuel for typical 25MPa concrete in Australia
- Transportation – all trucks are assumed to be articulated, loaded one-way, empty return and distance is from nearest suppliers.
- Transportation distance – Transportation distance may vary depending on the location of raw material suppliers. Ancillary materials (sand, gravel, NaOH, sodium silicate, fly ash, slag etc.), are assumed as following:
    - Sand/stone are quarried and processed on outer extremities of the city fringe. Transportation distances are estimated 500km including return appropriately.
    - Fly ash/slag is sourced from interstate and thus an additional road/rail transport of 1000km (such as Sydney) is assumed.
    - Sodium silicate is made in Melbourne and road delivery is estimated 100km including return.
    - NaOH is supplied from Melbourne thus, assumed 100 km of road distance including return.
    - Admixture is made in Melbourne and road delivery estimated 100 km including return.

To calculate the EEG, 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 8 shows a typical process flow for dry process bagged cement used for mortar.

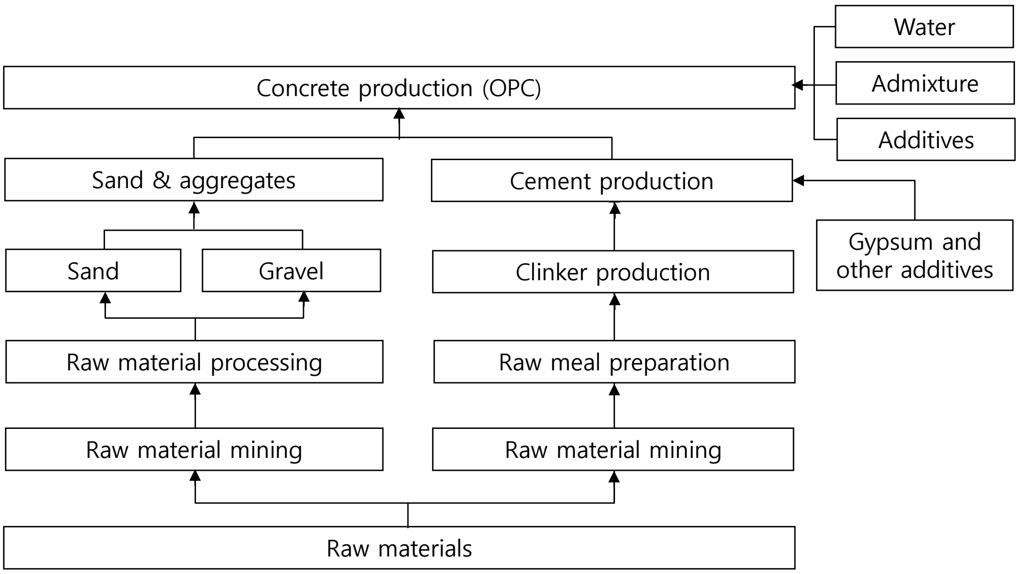


Figure 8 Process map for OPC

Based on the process map, the input/output data for targeted product are developed in the SimaPro model to calculate EEG.

SimaPro distinguishes five process types (materials, energy, transport, processing, use, waste scenario and waste treatment) each of which can be either a unit process, i.e. describing a single operation or a product system describing a set of unit processes as if it is one process.

The basic model of OPC concrete production cycles can be built as a single box process. Since the software only allows the creation of processes with quantified product output flow, a unit of product output is used for each process.

The input to produce 1000 kg of OPC are shown in

Table 6. Based on this input table, embodied impacts are quantified. Figure 9 shows schematic diagram how to quantify the embodied impacts. The input data shown in Table 4 are allocated in the existing LCI data (1st and 2nd column in Figure 9). Then, each inventory output data are classified into each impacts (GWP for EG as kg-CO_{2eq} and Energy for EE as MJ). And finally classified output data are multiplied characterisation factor to aggregate single indicator for embodied impact.

Table 6 Unit processes included in OPC concrete (1000kg)

Process name	Amount	Unit	Note
Cement (Portland)	93.8	kg	Australian cement industry data (2006)
Sand	350	kg	River
Gravel (crushed)	591	kg	Crushed river gravel used for aggregate
Transport (sand and soil truck)	54.1	m^3-km	For gravel and sand transportation
Blast furnace slag (steel plant)	18.7	kg	CSR data-specific (Australia)
Water	87.5	Litre	
Transport (articulated truck)	9.38	ton-km	For cement transportation
Transport (articulated truck)	15	ton-km	For slag transportation
Electricity (Australian average)	2.5	MJ	Australian average power data
Diesel fuel	8	MJ	

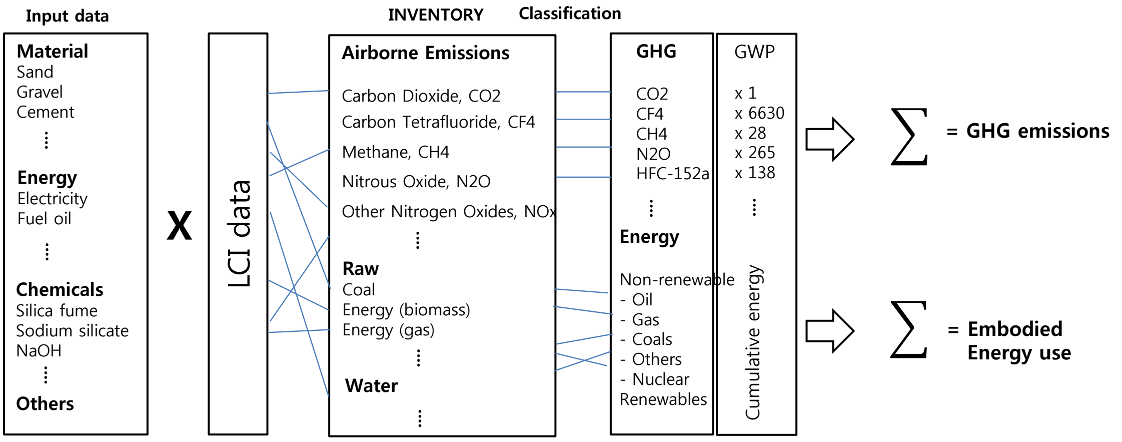


Figure 9 Example procedure of LCI outputs and their use in embodied impacts assessment

Table 7 and Table 8 show the results of EEG of the example case. As seen in the table, most energy is sourced from fossil fuels (i.e., oil, gas and coal) accounting for more than 99% of total energy consumption.

Table 7 EE for 1000 kg of product (MJ/1000kg)

Energy	Ordinary Portland Cement Concrete
Renewables	1.11
Fossil Fuel (oil)	98.6
Fossil Fuel (gas)	284
Fossil Fuel (coal)	397
Fossil Fuel (other)	0.0
Nuclear	0.0
Other/Unknown	0.0
EE	780.7

Table 8 shows total GHG breakdowns based on the different GHG which are emitted from the system to manufacture 1000 kg of each product. Here, CO_2 is a significantly contributor to the total EG, accounting for more than 98% of total GHG emissions.

Table 8 GHG emissions for 1000 kg product (kg-$CO_{2\ eq}$/1000kg)

GHG	Ordinary Portland Cement Concrete
CO_2	123
Methane	0.07
N_2O	0.001
Sequestration	0.00
Other/Unknown	0.058
EG	123.1

3.2.2 Input-Output analysis

3.2.2.1 Introduction

The Input-Output (IO) analysis method is an 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 GHG emission intensity of a given sector can be calculated. The IO-based intensities are obtained as the averages of relevant industrial sectors. In the US or Canadian IO table, the number of industrial sectors reaches nearly 700, thus enabling detailed economic analyses to be conducted. On the other hand, the South Korean or Japanese IO table contains approximately 400 sectors. The number of sectors is between 100 and 200 for other countries such as Thailand, Australia and Denmark, but it is still useful in calculating energy and carbon intensities. However, in countries where the IO table is based only on 60 or less industrial sectors, the building sector and the civil engineering sector are treated together as the "construction sector".

There are two proposed models of IO 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 the make-use model is used by countries such as the US and Canada.

3.2.2.2 Calculation method

The IO tables of each country are generally produced by national agencies. However, energy consumption and GHG emission intensities cannot be estimated only with the use of IO tables. Relevant energy tables or transaction tables are required. The WIOD (World-IO Database) (2015) provides IO tables in a uniform format, covering the period after 1995 regarding 40 countries across the world. The detailed data on annual GHG emissions can also be obtained from other references (WIOD, 2015; Boden et al., 2013).

In IO tables, interrelationships between industrial sectors are quantified on an activity basis, whereby the inputs of products to an applicable industrial sector are clearly indicated. Interrelationship diagrams can also be drawn up.

3.2.2.3 Example: Embodied impact intensities of building and construction industry sub-sectors (Japan)

An IO analysis method based on the Japanese context, as an example, is illustrated here, using a competitive import-type inverse matrices. Although the IO table is compiled as a 520×407 matrix (make use table), it is reformatted to a 401 × 401 square (symmetric) matrix by integrating the unmatched industrial sectors between rows and columns. Based on the postulation that competitive import-type inverse matrices are commonly used, the following equation is used for the calculation of competitive import-type inverse matrices.

$$X = \{I - (I - M)\,A\}^{-1}\ \{(I - M)\,F_D + F_E\} \tag{1}$$

where

X: Domestic output (JPY/year)

$\{I – (I – M) A\}^{-1}$: Leontief competitive import-type inverse matrix (-)

I: Unit matrix (-)

M: Import coefficient diagonal matrix

$m_i = M_i/C_i$

m_i: Import coefficient (-)

M_i: Import of i product (JPY/year)

C_i: Domestic demand of i product (JPY/year)

A: Input coefficient (-)

$F_{(D)}$: Domestic final demand (JPY/year)

$F_{(E)}$: Export (JPY/year)

In equation (1), the Leontief inverse matrix is calculated and the domestic final demand is included in the calculation. Therefore, the ultimate domestic output X, in which ripple effects have been taken into consideration, can be estimated.

Since the energy consumption and total domestic output data in each industrial sector is published, the energy intensity E_i (MJ/JPY) for each industrial sector can be derived. The total ultimate energy consumption E_F with final influences, thus, can be expressed with X_{ci} and E_i as follows:

$$E_F = \sum_{i=1}^{n} X_{ci} \times E_i \tag{2}$$

where,
n: Number of industrial sectors in the country (Japan)
E_i: Energy intensity (MJ/JPY)
X_{ci}: Domestic output in industrial sector i caused by $F_{(D)}$ for construction calculated with equation(1) (JPY)
E_F: Total ultimate energy consumption for construction (MJ)

The total ultimate CO2 emissions, C_F can be obtained in the same way as E_F by substituting GHG intensity E_G (kg-CO_{2eq}/JPY) for E_i (MJ/JPY). E_F and C_F mean EE and EG. X_{ci} is calculation result with $\mathbf{F}_{(D)}$ for construction.

The EEG for construction and building industry sector can be obtained for other countries using this IO approach. For the application of IO analysis to other OECD countries, please see the example in Chapter 4.

Transaction table

The transaction table lists the prices and quantities regarding 134 kinds of commodities consumed in individual industrial sectors. These quantities are divided by the domestic output (*X*) to obtain the consumption factors of these commodities. If we suppose that there is an input of 1 million yen (m¥) to *i* industry as the domestic final demand and, including the ripple effects, the ultimate domestic output (*X*) is estimated. Because the quantities of consumed commodities are considered to be proportional to the domestic output, each consumption factor is multiplied by the estimated domestic output to determine the final quantities of consumed commodities.

Energy consumption and GHG emissions are also calculated based on the consumed quantities of fossil fuels given in the transaction table. When oil product imports are too large to ignore, the quantities of fossil fuels consumed by a relevant industry in the transaction table are used. In utility power generation and some of the petrochemical industrial establishments, however, crude oil is directly consumed. Therefore, in addition to oil products, crude oil is included in the calculations of these industries. The GHG emissions as a result of limestone consumption in cement manufacturing are assumed to be 0.44 kg-CO_2/kg. The calorific values of fuel types consumed in a given industry and their GHG emission factors (shown as Table B1 in Appendix B) are used as the multipliers for calculation of energy consumption and GHG emissions, respectively.

Intensity tables

The intensities calculated according to the method described above are shown in Appendix B (Table B2). These intensities denote energy consumption or GHG emissions per 1 million yen (m¥) of the consumers' price. Although the table does not indicate the intensities of distribution margins (wholesale, retail, railway/road/sea transportation, port facilities and warehouses), these can also be calculated. Use of these intensities enables the estimations of energy consumption and GHG emissions resulting from transportation of construction processes.

3.2.2.4 Other considerations: Economic sectors related to buildings in IO tables

The number of building-related intensities depends on the organization of the IO accounts, which varies across the globe. Although there are a total of 401 industrial sectors in Japanese IO tables, only 169 of these are directly related to buildings. In the symmetric tables of World-IO, the number of industrial sectors is 35 and of these, 14 are directly related to buildings (WOID, 2015).

3.2.3 Hybrid analysis

3.2.3.1 Introduction

The hybrid method integrates the different features of the two methods above into one single approach, and thus inherits the benefits of both (Acquaye, 2010; Alcorn and Baird, 1996; Suh et al., 2003). It, however, also combines the challenges of each of the two methods.

The hybrid method either starts with an IO table and further details certain economic sector data by adding process data that pertains to specific manufacturing processes, or it starts from a process LCA and adds inputs for which no process LCA data are available. Although the hybrid method is usually undertaken to achieve the best quality and highest level of comparability in the results, compared to a pure process-based LCA or IO approach alone, the quality of the results depends on the availability and quality of primary and secondary data in both the process method and the IO table.

The subsequent sections describe in greater details the two types of hybrid methods introduced herein: the process-based hybrid analysis and the IO-based hybrid analysis. We note in the outset that some people do not consider the former as a form of hybrid, especially since the main data requirements and methodology follow the process based approach more closely.

3.2.3.2 Calculation method

Process based hybrid (PH) analysis

In a process-based hybrid (PH) analysis, the IO-based data are integrated into a process-based calculation framework to enhance the completeness of the calculation. For instance, when computing the PH EE of a building using a basic PH analysis, the building material quantities are collected from the bill of quantities and multiplied with their PH EE intensities. Using actual material quantities provides study-specific results. Material-specific waste factor may be applied to accommodate any material wastage occurring on the construction site. The following equations are used in a basic PH analysis (based on Crawford, 2004):

$$E_{bldg,indirect} = \sum_{i=1}^{n} Q_i \times E_{i,ph} \times WF_i \tag{3}$$

$$\boldsymbol{E_{i,ph} = EE_{i,p} + \left(T_{n,io} - T_{i,io}\right) \times Price_i} \tag{4}$$

$$E_{bldg,direct} = D_{m,io} \times Price_{bldg} \tag{5}$$

$$\boldsymbol{E_{bldg,ph} = (E_{bldg,indirect} + E_{bldg,direct}) \times PEF} \tag{6}$$

$$\boldsymbol{WF_i = (1 + \frac{Quantity\ of\ the\ wastage\ of\ material\ “i”}{Total\ quantity\ of\ material\ (“i”)\ use})} \tag{7}$$

where:

$E_{bldg,indirect}$:	Total indirect energy of a building (MJ)
Q_i:	The total quantity of material “*i*” (kg)
$E_{i,ph}$:	Process-based hybrid EE of material “*i*” (MJ/kg)
WF_i:	Waste factor of material “*i*” (dimensionless constant)
$EE_{i, p}$	Process-based EE of material “*i*” (MJ/kg)
$T_{n, io}$	Total energy intensity of sector “*n*” manufacturing material “*i*” (MJ/$)
$T_{i, io}$	Total energy intensity of IO path of material “*i*” (MJ/$)
$Price_i$	Price of material “i” ($/kg)
$E_{bldg, direct}$:	Total direct energy consumed in building construction (MJ)
$D_{m, io}$	Direct energy intensity of IO sector representing the building (MJ/$)
$Price_{bldg}$	Total price of the building ($)

$E_{bldg,\,ph}$	Process-based hybrid EE of the building (MJ)
n:	Number of materials in the building
PEF	Primary energy factor/s of the fuel supply

While calculating the PH EEG intensities of construction materials it is important to subtract the amount of energy equivalent to the process energy data from the IO-based total energy coefficient. For this reason, in Equation 4, the IO-based total energy intensity of a construction material ($T_{i,\,io}$) equivalent to its process-based EE is subtracted from the IO-based total energy intensity ($T_{n,\,io}$) of the industry sector to avoid energy double counting. It is important to note that Equation 6 uses PEFs (Primary Energy Factors), and in such cases, all energy and non-energy inputs to the energy providing sectors of the IO model are kept at zero in the hybrid IO model. Treloar (1997), Crawford (2004) and Acquaye (2010) provide further details about PH analysis.

IO based hybrid (IOH) analysis

The IO-based hybrid (IOH) analysis involves improving the reliability and specificity of an IO model by integrating more process data and disaggregating industry sectors. Various versions of an IO-based hybrid analysis have been proposed in literature (e.g. Carter et al., 1981; Treloar, 1997;1998a; Crawford, 2004). Each of the versions demonstrated an incremental improvement of reliability and specificity. In the first instance, Carter et al. (1981) proposed to integrate energy use data of each industry sector in an IO model. This method is particularly useful when energy use data of all industry sectors are available. In addition, it circumvents using unreliable energy prices to convert IO-based energy intensity from monetary to energy units (e.g. $/$ to MJ/$). Later, Treloar (1997) proposed another method to systematically extract direct energy paths from IO model for which comparable process data were available. Treloar (1997) also highlighted the issue of energy double counting and proposed to use primary energy factors when computing IOH-EE. Crawford (2004) identified some issues with the Treloar's methods and proposed an alternate IO-based hybrid approach, which, instead of direct energy paths, involved extracting total energy paths. Later, Acquaye (2010) reconfirmed extracting the energy of direct energy paths as originally proposed by Treloar (1997). Because an IOH method is based on the IO framework covering the entire economy, it has a wider system boundary than other hybrid methods. Only inputs for which no monetary transactions take place may remain excluded from the IO framework. Much of the efforts, therefore, focus on improving the reliability by integrating more process data and avoiding the use of unreliable energy prices. Joshi (1998 and 1999) proposed a technique to disaggregate an industry sector of the IO accounts using detailed input or output data. Joshi's technique can be integrated into the IOH method to compute material-specific EE. There are two types of IOH calculations (based on Carter et al., 1981; Treloar, 1997; Crawford, 2004; Acquaye, 2010; Dixit et al., 2015):

- IOH method based on direct energy path extraction

  This method represents a further development of the PH method discussed in the above. The only incompleteness contained in Equation (8) is of the indirect inputs to the main construction sector. Equation (8) can be modified to add these missing inputs by using the IO-based direct and total energy coefficients. The following equation can be used to compute the IOH-EE of a building:

$$\boldsymbol{E_{bldg,ioh}} = \boldsymbol{E_{bldg,ph}} + \left[\left(\boldsymbol{EI_{bldg,total,io}} - \sum_{i=1}^{n} \boldsymbol{EI_{i,direct,io}}\right) - \boldsymbol{EI_{bldg,direct,io}}\right] \times \boldsymbol{Cost_{bldg}} \quad (8)$$

$$\boldsymbol{EI_{bldg,total,io}} = \sum_{e=1}^{E} \boldsymbol{TC_{e,bldg}} \times \boldsymbol{Price_e} \times \boldsymbol{PEF_e} \tag{9}$$

$$\boldsymbol{EI_{bldg,direct,io}} = \sum_{e=1}^{E} \boldsymbol{DC_{e,bldg}} \times \boldsymbol{Price_e} \times \boldsymbol{PEF_e} \tag{10}$$

Where:

$E_{bldg,ioh}$:	Total IOH-EE of a building (MJ)
$E_{bldg,ph}$:	Total PH-EE of a building from Equation 4 (MJ)
bldg:	Represents construction sector in the IO model
$E_{bldg,direct,io}$:	IO-based direct energy intensity of construction sector (MJ/$)
$E_{bldg,total,io}$:	IO-based total energy intensity of construction sector (MJ/$)
$Cost_{bldg.}$:	Total cost of the building ($)
$EI_{i,\ direct,\ io}$:	IO-based direct energy intensity of the energy path representing material "*i*" (MJ/$)
n:	Number of materials in the building
$TC_{e,bldg}$	Total energy coefficient for energy inputs from "*e*" to "*bldg*"
$DC_{e,bldg}$	Direct energy coefficient for energy inputs from "*e*" to "*bldg*"
$Price_e$	Energy price of energy source "*e*"
E	Number of energy sources used
PEF_e	Primary energy factor of energy source "*e*"

As mentioned previously, it is important to note that the above Equations (9) and (10) use PEFs, and in such cases, all energy and non-energy inputs to the energy providing sectors are kept at zero.

- Integrating sectoral energy use in IO model

This method is simpler than the earlier method and is based on Carter et al. (1981). If the total energy usage of each industry sector of the economy can be determined in physical units (e.g. MJ or MBtu), it can be directly inserted into the IO model. In this method, the calculated direct and total energy requirements are in physical units/output (e.g. MJ/$). The conventional IO model provides the direct and total energy requirements in $/$ units, which requires the use of unreliable energy prices decreasing the reliability of the calculation method. In this method, the calculation avoids using energy prices increasing the reliability of IOH calculation. If the energy embodied in labour and capital inputs can be determined for each industry sector, these data can also be integrated as separate energy commodity in an IO model as demonstrated by Dixit et al. (2015).

The United States' IO accounts are published with asymmetrical Make and Use tables, which list the production and consumption of commodities in the economy, respectively. In Use table, the $ values of energy commodities in rows can be replaced with the actual energy consumption of each industry in physical units. If the energy embodied in labour and capital inputs is quantified, these values can also be inserted in the Use table as rows representing two new commodities. Because Make tables show the portion of commodities manufactured by each industry sector, no modification may be required. Using the modified Use and Make table, the direct and total requirements can be quantified in energy units (MJ/$) as follows:

$$\mathrm{A} = \mathrm{U}\hat{\mathrm{i}} \times \{(\mathrm{M}\hat{\mathrm{c}}) \div \mathrm{R_s}\} \tag{11}$$

$$\mathrm{R_s} = O_s \div O_t \tag{12}$$

$$\mathrm{T} = (\mathrm{I} - \mathrm{A})^{-1} \tag{13}$$

where:

A: Direct requirement coefficient matrix (energy providing sectors in energy units)

$\hat{\mathbf{i}}$: Industry output vector

$\hat{\mathbf{c}}$: Commodity output vector

U: Modified use matrix (from Use table)see

M: Make matrix (from Make table)

R_s: Non-scrap ratio

O_s: Industry output with scrap

O_t: Industry output without scrap

T: Total requirement coefficient matrix (energy providing sectors in energy units)

I: Identity matrix

The total requirements can also be calculated using the power series approximation (PSA) method for each indirect stage (Dixit et al. 2015). According to Treloar (1997) and Miller and Blair (2009), indirect inputs calculated up to stage 12 can cover nearly all of the indirect energy.

Example: Embodied impact intensities of building and construction industry sub-sectors (US)

Depending on how the IO accounts are organized, a number of construction-related sectors or commodities can be identified. For instance, in the United States' IO accounts, seven sectors directly relate to construction activities.

There exist other sectors that supply indirect inputs such as construction materials, equipment, automobile, software, labour, and required services. These sectors are numerous and can be identified based on a building's bill of quantities. The number of directly and indirectly-related industry sectors and their level of disaggregation in IO accounts will change with the geographic location of a study.

3.2.3.3 Other considerations

Process based hybrid analysis

Because this method is based on a unified process and IO-based model, it also contains some of their limitations. For instance, the system boundaries of the process-based intensities of construction materials may not always be known, particularly if the data are collected from a secondary source. In such a case, it is difficult to determine how much energy should be extracted from the IO-based total energy intensity as calculated by Equation 4. In addition, the used process-based intensities may not be complete causing an error in the calculation. When Equation 3 is used for computing the total EE of a building, the indirect energy associated with the construction sector (e.g. construction services) remain excluded from the calculation.

A conventional IO analysis suffers from the problem of counting energy multiple times as demonstrated by Treloar (1997) and Dixit et al. (2014). This issue is found not only in the case of energy providing sectors but also other sectors distributing energy sources. For instance, if a retail sector buys and resells a large quantity of certain energy products, all of the energy bought would be considered the sector's energy consumption according to IO theory, which is inaccurate. When computing the IO-based total and direct energy intensities of construction materials, keeping all energy and non-energy inputs to energy providing sector at zero is recommended to avoid the issue of energy double counting. These energy and non-energy inputs can later be added by computing and using primary energy factors (Treloar, 1997; Dixit et al., 2014). As discussed in the earlier section on IO analysis, the energy embodied in labour and capital inputs (e.g. plant, automobile, and equipment) is also not covered by a PH analysis. Although PH-EG can be used to quantify the resulting GHG emission, any emission that is non-energy-related may not be included.

IO based hybrid analysis

As mentioned above, the IOH calculation carries with it the limitations of the conventional process and IO analyses. Because the framework of an IOH analysis is primarily IO-based, it may include some errors resulting from proportionality and homogeneity assumptions on which the IO accounts are based. A proportionality assumption considers that the proportions of inputs required for producing a product or service is the same across the industry, which may not be realistic. Under homogeneity assumption, it is assumed that the input mix of a product is homogeneous across the industry.

Because most IO accounts may not include the capital inputs, it is important to determine and insert them into the IO model. Similarly, because household expenditure is external to an IO model, the energy embodied in labor may remain excluded from an IOH calculation. To account for the energy embodied in labor, the labor inputs of each sector can be quantified using worker population and expenditure data (Dixit et al. 2015).

Other important aspects include the issue of the double counting of energy inputs and the usage of unreliable product prices. The issue of double counting can be resolved by using the PEF approach suggested by Treloar (1997). However, the IOH method still results in energy intensities of industry sectors in energy units/unit of output (MJ/$). To convert the energy intensities to EE values per unit of mass or volume (MJ/kg or MJ/cubic meter), material prices may be needed, which may not be reliable.

3.3 Comparison of methods

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 in reducing the effort to quantify the EEG of buildings.

Establishing background process based LCA databases is as time consuming as establishing environmentally extended input output databases. The system boundary and cut-off criteria, the availability of company or sector specific reliable and transparent data are the 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 EEG 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 IO table are available, the two approaches (process based and IO based) may not differ substantially. However, a building's EEG may differ depending on the approach chosen.

That is why, the publication or supply of embodied impacts data should clearly specify the calculation method used. The main recommendation is to avoid mixing up data sets from the different calculation methods and/or comparing results from two or three different approaches, without understanding their differences and background assumptions. In other words, it will be inappropriate to compare product/building A, which has an embodied impact calculated using a process based approach with an alternative product/building B, which has an embodied impact calculated using an IO approach.

Table 9 to Table 11 summarises and compares the key characteristics of each method, including relative advantages and disadvantages. In the next chapter, guidance on preparation of databases based on these methods, and a summary of commonly available embodied impacts databases in selected parts of the world are presented.

Table 9 Summary of embodied impact calculation method - Process based LCA

Method	Process method
General description	Collecting and linking data for specific unit processes to model the environmental impacts of products or services over their life cycle. Each process is represented by inputs of products/servcies from other processes as well as elementary flows (resource inputs and emissions to air, water and soil) • Detailed granular level (i.e., material, product, building etc.) • Usually it does not cover service sector inputs such as building insurance, planning processes and the like because of their minor importance.
Relevant guidelines and/or standards	ISO 14040, ISO 14044, ISO/TS14067 UNEP SETAC ISO21930 EN15804, EN15978 PEF guide (European Commission 2016) etc
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
Data output	kg-CO_2 emitted, kg of hard coal extracted etc per product or building
Calculation approach	Life cycle inventory matrix nversion or sequential accumulation
Examples	Ecoinvent (see e.g., Frischknecht et al., 2005), etc.
Advantages	• Sourcing of primary data is easy and affordable • Detailed and accurate approach to quantify the cumulative energy demand, GHG emissions and further environmental impacts of producing a material, component or building, including transportation, waste management etc. • Provides robust “hot spot” information that can be used to improve environmental performance of building or building product manufacturing. • Well documented methodology and guidance • Widely accepted across different disciplines, industry sectors and stakeholder groups
Disadvantages	• Sourcing of primary data may be more laborous and time consuming in some countries.
Database development, maintenance & management	• Development as described in section 4.2.2 • Maintenance and management involve keeping the temporal and technological representativeness of the established database current.

Table 10 Summary of embodied impact calculation method – IO analysis

Method	IO analysis
General description	An economic approach which uses sectoral monetary transactions data (national input output data) to account for the complex interdependencies of industries in economies. Energy consumption and/or GHG emission intensity of a given economic sector are calculated by linking this with statistical information on energy demand or GHG emissions for the same sectors. The IO-based intensities are obtained as the averages of relevant industrial sectors. • Can cover macro level (building, urban, industry etc.) • Usually covers all economic activities, including services, advertising, and the like.
Relevant guidelines and/or standards	UNEP (UN, 2000 #5301)
Data input	National statistics on annual sectorial production (physical and monetary), ports, exports, investments and consumption National statistics or information on inter-sectoral 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 sector based on matching tables and assumptions
Data output	kg-CO_2, MJ etc per monetary based ($)
Calculation approach	Economical input-output matrix inversion
Examples	3EID, Carnegie Mellon EIO LCA, CREEA (Tukker 2014 #5298) etc.
Advantages	• Sourcing primary data may be easier or less costly in some countries (generally available from national statistics center); thus, a good starting point in industry sectors or countries that lack detailed process data • Data is relatively easy to update • Completeness – takes into account cross-industry interactions; or, can include ripple effects and transportation and margins in calculation of intensities • Able to estimate the intensities of facility equipment or the like because calculations are performed on a price basis,
Disadvantages	• Lack of temporal representativeness • Different structure and level of details in IO tables from different countries in the world (including different definition or disaggregation of industry sectors) • Difficult to disaggregate from given IO table sectors into sufficient range of materials used in building and construction (decisions can be very subjective) • Inability to reflect differences between materials because the intensities are the averages of a given industrial sector • Can be misused when lacking sufficient knowledge of IO tables (e.g., foamed insulants fall within a category of plastic products, but may be considered as thermoplastic resins by mistake) • Difficult to handle by-products. • Potential for double-counting • Inaccuracies resulting from proportionality and homogeneity assumptions in IO accounts. A proportionality assumption considers that the proportions of inputs required for producing a product or service is the same across the industry, which may not be realistic. Under homogeneity assumption, it is assumed that the input mix of a product is homogeneous across the industry. • Most IO accounts may not include the capital inputs, it is important to determine and insert them into the IO model. Similarly, because household expenditure is external to an IO model, the energy embodied in labor may remain

	excluded from an IOH calculation. To account for the energy embodied in labor, the labor inputs of each sector can be quantified using worker population and expenditure data (Dixit et al. 2015).
Database development, maintenance & management	• Development as described in section 4.2.3 • Database creation involves not only IO-based calculations but also result verification, which may be time-consuming. The time required is different between completely new IO tables and those with similarity. • The industry classifications and patterns of energy production and usage by industry sectors change over time. Calculations should reflect any such changes (e.g. the values of PEF due to changing fuel mix need to be recalculated annually) • In Japan, the latest IO tables are prepared and made publicly available every 5 years. World-IO provides IO tables for each year. Therefore, IO-based intensities can be updated every 1 to 5 years. • In the US, the summary level IO data are published each year by USBEA. However, the detailed benchmark data are published after five years. To obtain more recent data, private sources such as Implan Inc. can be used.

Table 11 Summary of embodied impact calculation method – Hybrid analysis

Method	Hybrid analysis
General description	Combined process and IO approach.
Relevant guidelines and/or standards	No standard or guideline but similar to "process method" except for granular level of data (IO data used for granular level)
Data input	Process data LCI data Economic data Economic input-output data
Data output	kg-CO_2, MJ etc per product or building based
Calculation approach	Combined "Process" & "IO" methods
Examples	Scientific papers from universities
Advantages	• Provides a more complete assessment than the values of a process-based analysis alone • More-specific results to a product under study than an IO-based method alone.
Disadvantages	Contains some of the individual method's limitations (see columns on the left). For instance: • the system boundaries of the process-based intensities of construction materials may not always be known, particularly if the data are collected from a secondary source. In such a case, it is difficult to determine how much energy should be extracted from the IO-based total energy intensity • the used process-based intensities may not be complete causing a serious error in the calculation.
Database development, maintenance & management	• Depends on the availability of basic LCA-based and IO databases • Updating the hybrid model becomes important as soon as the new IO accounts are published. The organization and structure of IO accounts may also change over time, and in such cases, the IOH database needs to be updated. c

4. Databases

4.1 Overview

The quantification of primary energy consumption and GHG emissions of buildings and construction works usually relies on background data quantifying the primary energy consumption and GHG emissions of either construction materials and technical equipment such as electric wiring, water supply tubes or ventilation systems (process based LCA data) or of economic sectors from which the construction materials, the technical equipment and any further services are purchased from (data from input output tables extended with primary energy and GHG emission intensities or, more generally, environmentally extended input output tables).

Within the process based LCA databases one may further distinguish between databases providing datasets on a unit process (gate to gate inventory information, see Figure 10, left) basis, on the basis of aggregated (cradle to gate life cycle inventory results, see Figure 10, right) processes or on the basis of a selection of environmental indicator results (cradle to gate life cycle impact category indicator results, e.g. EPD based databases or the KBOB-recommendation 2009/1:2014, 2014). It is important to emphasise the fact that databases providing environmental indicator results may also and additionally provide LCI results and/or gate to gate inventory information.

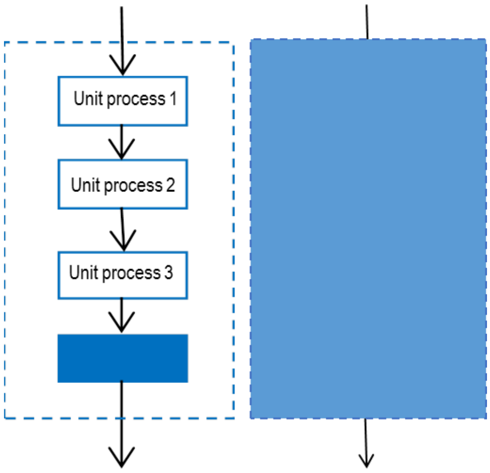


Figure 10 Unit process life cycle inventory dataset (left) versus aggregated life cycle inventory dataset (right)

Within environmentally extended IO databases one may distinguish between single national IO databases and multiregional IO databases, the latter linking dozens of harmonised national input output tables to one large regional IO table (see e.g. (Tukker et al., 2014)).

The main families of EEG databases, or databases useful for embodied impacts calculation are:

- unit process LCI databases
- aggregated process LCI databases
- EPD-results databases
- national environmentally extended IO databases
- multiregional environmentally IO databases

4.2 Main steps towards EEG databases

4.2.1 General

This section deals with the content related aspects of creating EEG databases. Organisational issues such as funding, organisational setup, milestones, monitoring and the like are out of scope of this section. In the following two sections, process based LCA databases and IO databases are covered separately. A comprehensive guideline document for the former has been jointly published by UNEP-SETAC (Sonnemann and Vignon 2011).

4.2.2 How to establish a process based LCI database

The creation of a new process based LCI database, which is (also) suited to support the energy and climate change impact of building, involves the following main steps.

- Economic sectors to cover: sufficiently comprehensive databases comprise data on energy supply, materials supply (including forestry, and agriculture), transport services and waste management services.
- Detailed list of energy carriers, materials, transport services and waste management services: once the sectors are determined, a detailed, one by one list of datasets is established, for which data are being collected and which are available for all others to link to (e.g. a concrete dataset is provided and at the same time required by energy supply datasets as hydroelectric power stations have a concrete input for their construction phase).
- Environmental impacts to be addressed: it may make sense to be comprehensive and to include more than just energy resource extraction and greenhouse gas emissions. In view of the trend towards to reporting a comprehensive set of environmental impacts related to construction materials, the effort to collect energy and greenhouse gas emission figures can be used to ask for further environmental information.
- Data inquiry: questionnaire listing the information need when collecting data from producing industries.
- Database and dataset protocol: the protocol describes the relevant rules with regard to what information and which data to collect, how to deal with data gaps and missing information (data), which cut-off criteria to apply, how to deal with co-production and recycling (allocation), which electricity mix to choose, what additional (describing) information to provide, how to name processes and pollutants, what units to use, how to quantify data uncertainty and how to report data quality assessment, etc. The ecoinvent methodology report (Frischknecht et al., 2004; 2007) is a good example of a database protocol.
- Calculation routines: determine the way how life cycle inventory results are being calculated. Main approaches are sequential calculation including a conversion and cut-off criterion and matrix approach on the other (see e.g. (Frischknecht et al., 1995; Hedemann, J. and U. König, 2003). The matrix approach is also used in calculating cumulative greenhouse gas emissions of economic sectors with an environmentally extended I/O table.
- IT infrastructure (e.g. LCA software or LCA database system): data on LCA datasets are to be stored and managed in a central IT infrastructure (either tailor-made or existing). This ensures consistency in that all datasets are interlinked properly and changes in data of one dataset are propagated into all other datasets.

When establishing an LCI database several key challenges need to be addressed as described in Frischknecht (2006). The three main requirements on the way to a joint LCA database are:

- LCA institutes and consultants, LCA funding bodies and industry should seek national and international co-operation to gain synergies and to share work.

- Strive for a consensus on LCI modelling conventions and flow reporting conventions within your database initiative and classify subjective LCI methodology issues to a few standard choices.
- Strive for consensus on environmental impact characterisation, but allow a variety of approaches in normalisation, grouping and weighting, including time preference.

The main methodological choices in LCI modelling deal with the following three questions:

- Whether to model an average situation of the (recent) past or a decision situation. In the latter case changes due to a decision are modelled rather than a (current or past) state.
- How to deal with allocation and recycling (mere allocation approach or granting credits for potentially avoided production)
- Whether or not to transparently report the unit process data and their inter-linkages.

4.2.3 How to establish an environmentally extended IO database

The creation of a new environmentally extended IO table, which is (also) suited to support the quantification of the primary energy demand and the climate change impacts of buildings, involves the following main steps.

- Define the economic sectors to be addressed individually: this list of sectors is mainly given by the national statistical department. In view of interlinking several national IO tables, aggregation or regrouping of selected economic sectors may be required. Furthermore, the allocation of companies to sectors may need adjustments as companies may have activities classified in different economic sectors whereas the economic data are reported for the entire company. Net benefits, margins, investments and taxes are other aspects which need special consideration.
- Quantify the economic interrelationships: the annual purchases as well as the annual production data (the latter in terms of monetary and physical units) are collected to populate the supply use table. The supply use table needs to be converted to a symmetric input output matrix. In case a multiregional IO table is established like within the Exiopol-projects (Tukker et al., 2014), a harmonisation of the different national IO tables is additionally required.
- Attribute the domestic emissions and resource consumptions to the economic sectors: this is a demanding and laborious step given the variety of statistical data available for pollutants emissions and resource consumptions and the partial mismatch of these statistics with the economic sectors usually available in IO tables. For instance, air pollutants such as NOx, particulate matter, heavy metal and the like are reported on an activity basis (e.g. fossil fuelled boilers of a certain size class), which does not fit very well with the economic sectors' structure of the IO table. Car emissions need to be distributed between the private consumption (using cars for commuting and leisure) and the use of cars in companies. The emissions data on certain pollutants such as waterborne emissions are attributed to the waste management sectors because they are released by waste water treatment plants. In such cases the emissions attached to economic sectors are attributed via payments related to waste water volumes rather than via the amount of pollutants sent to the sewer for treatment. If no domestic information is available, one might look for information from the same sector in similar countries. In several instances proxy allocation rules need to be applied as a last resort such as number of employees, total turnover of the sector and the like.
- Attribute the imports to the economic sectors: this is a similarly challenging task like the attribution of the pollutants emissions and resource consumption data. In general, the availability of sector specific information on what kind of goods and services are imported by which sector is even poorer than the availability of sector specific emission data. Data on the overall imports into a country, including information about the country of origin and the transport mode of the last transport activity (importing into a country) is usually available from the national

trade statistics. Also here, surrogate criteria such as number of employees or annual turnover are being used to allocate the total imports among the economic sectors (and partly consumption).

- Quantify the emissions and resource consumptions related to the (physical and service) imports: this is either done by (1) assuming that the imported goods are produced in the same way as domestic goods, (2) linking to the export section of respective national I/O tables, and (3) by combining import information with LCA data. By combining physical information on the amounts of imports and most representative LCA data on these imports, the emissions and resource consumptions of imported goods are quantified on a per kg and an annual basis (see e.g. (Frischknecht et al., 2008; Jungbluth et al., 2011). By selecting the most appropriate level of detail and depending on the comprehensiveness of LCA data available, the emissions and resource consumptions of imports can be quantified rather reliably. Hereby, the LCA data are often not covering all relevant countries of origin leading to approximations.

4.2.4 Synthesis

From the description of the procedures on how to establish process based and IO based databases for EEG one can derive that it is a laborious task in either case. Hence, such work should ideally be performed centrally (and regularly) in a country or region. It is not a primary task for companies and research institutes of the construction sector to take care of such a basic task. Hence, planners and architects should be able to build on the work of economists and/or LCA practitioners providing the basic information needed (process based LCA databases, environmentally extended IO databases) to successfully model the primary energy consumption and greenhouse gas emissions of building project alternatives.

4.3 Minimum Requirements on EEG 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 aluminium, 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 m2 usable surface basis. The energy supply data and the transport services data are used in modelling 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 (EE 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 R134a the eventual emissions of 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 embodied impacts 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)?

These requirements demand a professional operation and maintenance of LCA databases. The contents of the LCA database require continuous updates and a master plan on when and in which frequency such updates are due. The database management needs additionally to take into account national and international developments to ensure that the LCA database is suitable to cover new demands (in terms of new modelling requirements or new environmental impact category indicators). The increased demand for water footprint analyses for instance asks for a more comprehensive and sophisticated inventory of water inputs and water outputs as compared to five to ten years ago.

4.4 The role of standardisation

4.4.1 Overview

There are several international and European standards, which cover the topic of EEG. The following list mentions the ones most frequently (also) applied to buildings, construction works and building products:

- ISO 21930: Sustainability in building construction -- Environmental declaration of building products
- EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products
- ISO/TS 14067: Greenhouse gases -- Carbon footprint of products -- Requirements and guidelines for quantification and communication.
- ISO 21931: Sustainability in building construction -- Framework for methods of assessment of the environmental performance of construction works -- Part 1: Buildings
- EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
- Product environmental footprint (PEF): Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union.

The above mentioned standards differ in their requirements on modelling, in particular with regard to multifunctional allocation and recycling. This is further elaborated upon in the next section.

4.4.2 Modelling differences: allocation and recycling

The European standard EN 15804 (CEN 2013) “Sustainability of construction works – Environmental product declarations - Core rules for the product category of construction products” on core rules” requires to keep the benefits and loads beyond the system boundary (module D) separate from the environmental loads caused during the product stage (modules A1-A3), the construction process stage (modules A4-A5), the use stage (Modules B1-B7) and the end of life stage (modules C1-C4) of the construction product under analysis. The product stage shall be quantified respecting the actual amount of secondary material used in the product. The benefits and loads are quantified for the net amount of secondary material leaving the product system under analysis.

The product environmental footprint recommendation of the European Commission (2013) follows a complex 50%/50 % approach. 50% of the share of secondary material used in the product under analysis is modelled using the recycling process, whereas the remaining share is linked to primary material production. For 50% of the share of secondary material used a credit is granted for avoiding end of life treatment (such as incineration). 50 % of the share of secondary material recycled at the end of life of the product under analysis gives rise to credits due to avoiding primary material production. At the same time the environmental impacts of the end of life recycling efforts for this share are added.

In Table 12 the greenhouse gas emissions of 1 kg of an aluminium metal sheet are shown, when applying different allocation approaches, i.e. end of life or avoided burden approach, the recycled content or cut off approach (see Frischknecht (2010) for a description of these two), as well as the allocation approaches as specified in the Product environmental Footprint recommendation (EC, 2013) and in the European EPD standard EN 15804 (CEN, 2013). The greenhouse gas emissions of primary and secondary aluminium as well as the share of these qualities used in wrought aluminium alloys are based on information from the European Aluminium Association (EAA, 2013).

While the greenhouse gas emissions excluding credits are the same using the recycled content and the EN 15804 approaches, they are substantially higher in the other two approaches. EN 15804 does not allow for merging emissions and credits. The end of life allocation approach results in the lowest greenhouse gas emissions, whereas they are highest applying the recycled content approach.

Table 12 Greenhouse gas emissions of 1 kg of an aluminium sheet (façade) applying different allocation approaches; Basic data are sourced from EAA (2013)

1kg aluminum sheet (façade)		**End of life**	**Recycled content**	**PEF**	**EN15804**
Material supply		Kg CO$_{2eq}$	Kg CO$_{2eq}$	Kg CO$_{2eq}$	Kg CO$_{2eq}$
Recycled aluminum	0.46 kg	4.14	0.391	0.1955	0.391
Primary aluminum	0.54 kg	4.86	4.86	6.57	4.86
Disposal credits	0.46 kg	0	0	-0.0023	0
Manufacture	1 kg	0.6	0.6	0.6	0.6
Use	1 kg	0	0	0	0
End of life treatment					
EoL recycling	0.9 kg	0.765	0	0.3825	0.374
EoL recycling credits	0.9 kg	-8.1	0	-4.05	-3.96
Landfilling	0.1 kg	0.001	0.001	0.0055	0.001
Total, excluding credits		10.366	5.852	7.7535	5.852
Credits		-8.1	0	-4.0523	-3.586
Total, including credits		2.266	5.852	3.7012	not allowed

End of Life: credits for end of life recycling based on avoided primary aluminium production; recycled and primary aluminium on the input side modelled as primary aluminium

Recycled content: share of recycled aluminium in the product is modelled with recycled aluminium data, aluminium recycled at the end of life leaves the system without burdens nor with causing credits

PEF: recycling allocation according to the Product environmental footprint recommendation of the European Commission (EC, 2013)

EN 15804: recycling allocation according to the procedure described in clause 6.4.3.3 of EN 15804 (EC, 2013)

4.4.3 Environmental impacts covered

The standards and recommendations differ in the scope of environmental impacts to be covered. The climate change impacts indicator (greenhouse gas emissions) is covered by all standards and recommendations specifying the environmental indicators to be addressed. The indicator cumulative energy demand (renewable and non-renewable) is covered by the EN 15804 standard but not by the PEF recommendation. However, the PEF pilot project on photovoltaic electricity generation added these two indicators to the list of environmental indicators (Wyss et al., 2015).

4.4.4 Requirements on databases

None of the standards and recommendations prescribes the use of a particular LCI database. All of them however refer to process based LCA data (as opposed to environmentally extended IO data). The standards specify data quality requirements covering aspects such as maximum age of the data, minimum share of specific data to be used, etc.

There is one ISO standard on LCI data documentation format (ISO 2002). However, this standard does not address the technicalities of LCIA data format and is not prescriptive. Two inclusive data formats exist, the EcoSpold v1 (and v2) data format and the ILCD data format. Besides these two inclusive formats, several exclusive data formats are used in LCA software. Due to substantial content related differences (e.g., missing data fields in either of the formats, different approaches in grouping flow information) it is difficult to exchange data automatically between the two inclusive data formats mentioned above. Efforts to overcome these obstacles are ongoing within the Global Network of Inter-operable Databases[1]. Three working groups deal with issues such as LCA nomenclature, metadata descriptors, as well as network technology and architecture.

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[1] http://www.scpclearinghouse.org/working-group/54-global-network-of-interoperable-lca-databases.html, accessed 22 September 2015

The handbooks of national accounting of the United Nations statistics division published an operational manual on environmental accounting of nations ((UN & UNEP, 2000). Besides this, harmonisation of environmentally extended IO tables and databases is strived for in international research projects such as CREEA ([2]). Hence, research and co-operation rather than standardisation is the way towards consolidated and harmonised environmentally extended IO databases.

4.4.5 Implementing global warming potentials

Besides the standards on modelling and data format, the appropriate implementation of the global warming potentials as published by IPCC (2013) needs to be secured. In the latest version of the IPCC reports global temperature increase potentials (GTP) are published in addition to the well-known global warming potentials (GWP). Because LCA and EEG ask for an integrative measure, GWP remains the first choice. In the annex of Chapter 8, which contains the GWP and GTP values, GWP values of short term climate forcers (STCF) such as SO2, VOC, or PM are listed as reported in several research papers. The values published in the scientific literature and reproduced in this Annex vary considerably (from negative to positive) and the uncertainty in these values is highlighted in the text. Because no consolidated single values are shown for these STCF and because of the high variability in the values presented in the IPCC Annexes, it is recommended not to include these substances in the calculation of GHG emissions.

4.5 Stakeholder requirements

4.5.1 Introduction

The main stakeholders with regard to buildings and constructions are the building owners as well as the architects and engineers. All of them need to pay attention to many different needs, requirements and boundary conditions when planning, constructing and operating a building. In most cases they are not familiar with the complex topic of environmental LCA. Thus they must trust in relatively simple but reliable information.

That is why life cycle based environmental information needs to be prepared and simplified before submitted to building owners, architects and engineers. The information relevant for important national and international labelling schemes and programmes need to be provided. At the same time, traceability and transparency need to be guaranteed by publishing extensive background documents for experts. These documents help the reader to understand the way how the key environmental figures are calculated and modelled and which information sources have been analysed and finally used.

4.5.2 Example: the KBOB recommendation 2009/1:2014

The KBOB-recommendation 2009/1:2014 (2014) is one example of an easy to use LCA database for architects and engineers. 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 a 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 (see Figure 11). 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.

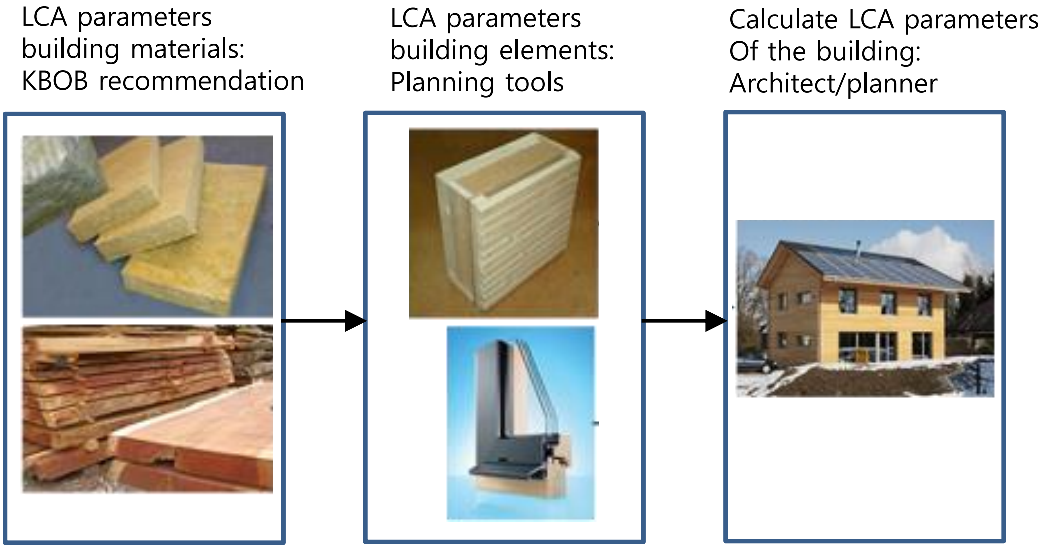


Figure 11 Division of tasks between LCA analysts, building software providers and architects/planners

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 GHG emissions, they are suited to support a variety of environmental impact category indicators (see Figure 12) 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).

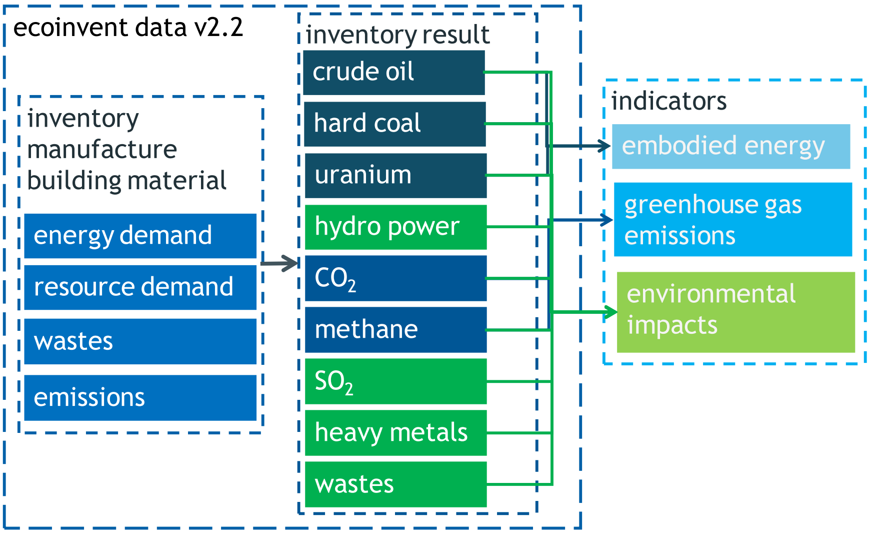


Figure 12 Connection between the unit process inventory data (left), life cycle inventory results (centre) and environmental indicators (right), shown on the example of the KBOB-recommendation 2009/1:2014 (2014)

A flexible and comprehensive LCI database forms a highly valuable basis for many different applications (see Figure 13). For instance, the ecoinvent data v2.2+ (KBOB, 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.

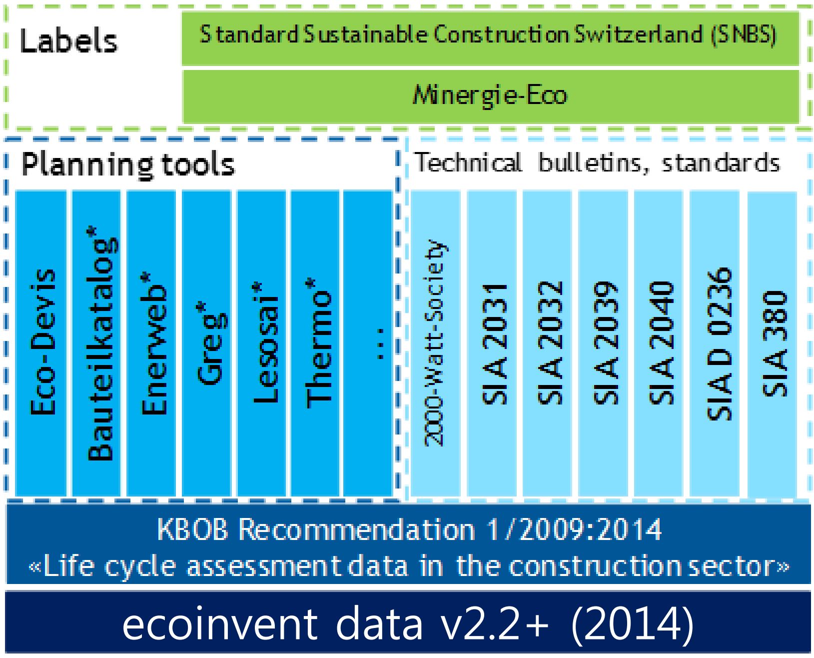


Figure 13 The comprehensive life cycle inventory database ecoinvent data v2.2+ (KBOB, 2014) forms the basis for the KBOB-recommendation 2009/1:2014 (2014), as well as several Swiss planning tools and technical bulletins and standards

4.5.3 Stakeholder's view on process LCA and IO databases

From a stakeholder perspective there are hardly any differences in using either process LCI databases or environmentally extended IO tables. Some aspects need to be taken into account however, in particular

- on the processing of the information (how to look on the database's contents).
- on the data required (producer specific when assessing and choosing suppliers; generic/average when designing buildings and evaluating alternative projects)

Change of databases needed if projects evaluation is done with IO data and later in the process suppliers are to be chosen or label for the building realised is aimed for.

4.5.4 Expectations on updates and extensions

The users (architects and engineers) of life cycle based information expect continuity in the indicator results as well as in the list of construction materials offered. Of course, substantial changes in the results may happen due to improved material efficiencies or newly installed emission control equipment. Such changes are easily explainable. However, care must be taken not to completely change modelling approaches and to switch impact category indicators which may result in completely different results, in particular on the level of the environmental impacts of buildings.

It is recommended to perform an in-depth quality control on updated and new life cycle inventories. The changes between the environmental impacts of existing and new versions of a dataset should be checked carefully and the reasons should be known and plausible. In case indicators as well as life cycle inventory data are changing at the same time, a stepwise quality control is recommended. Firstly, the changes due to the updated life cycle inventory data are explained, and secondly, the changes due to the change of the environmental indicator are addressed.

4.6 Overview on country specific EEG databases

4.6.1 Preliminary survey of EEG databases

Many countries have been developing or developed EEG data for building products. This study preliminarily surveyed EEG databases from the participants in Annex 57 countries. A total of seven questions are concerning three areas in the survey; methodology, management and other key consideration for EEG to understand what kind of database they use, which methodology is used for data, who maintains/manages the database, how to deal with EEG data for emerging products, transportation, recycled/reused materials, and how they consider on-site emissions. For the survey, a total 13 countries were responded from four different regions (Asia, Oceania, North America and Europe) (See Appendix C for preliminary survey of EEG, and Appendix D for EEG data for each countries).

In the survey, the response from most countries was that an EEG database exists but only as LCI data for building products. Thus, there is a need to covert the LCI data into embodied impact using impact assessments (GWP (IPCC 2013), total energy usage (Frischknecht et al. 2015), etc.). Also, many countries responded that the dominate methodology to quantify the EEG data was the process based methodology.

These databases have been developed and managed primarily by academic or private sector organisations (e.g., universities, research institutes etc.) except in Korea and Japan where the database is managed and maintained by a government agency.

Most countries responded that their EEG databases did not cover the emerging products but was rather more focused on general products. Emerging or specific products were covered if required, privately or with EPDs. EEG impacts from capital equipment are not included in the EEG data except for Japan, where a mingle process is used with IO based methodology in the official EEG data and Switzerland, where capital equipment are part of the process based LCIs.

Depending on the volume of the recycled or reused content for a manufacturing of building material, the EEG of a product may have a large variation for their value. Most of countries, in the preliminary survey, responded that they consider, if possible, recycled or reused content for their development of EEG database with industry average.

Most of countries consider transportation and on-site emissions in the EEG data, but it is not easy to consider all of these. This is appeared similarly for the construction waste. The Swiss data include transportation, on-site emissions and construction wastes.

4.6.2 EEG database for building materials

EEG data exists (e.g., ICE in UK, FWPA in Australia etc.) for building or building and construction products, but most of this data exist as LCI data format rather than EE or EG itself. Some of the databases (e.g. the Swiss one) offer all three levels of information: the Swiss database reports (1) direct inputs and outputs of a manufacturing process, (2) the cradle to gate resource extractions and emissions (LCI result), and (3) the cradle to gate cumulative energy demand, GHG emissions etc. (LCIA result).

Table 13 summarises the existing EEG databases which are publicly available from around the world. Since this report focuses on the building/building product, the table only lists databases which can provide EEG for building products.

Existing general LCI databases, which are used for general LCA studies, are not listed in the table. As shown in this table, a number of EEGor LCI database for building material/products exist in the world. These databases are based on different geographical boundaries, quantification method and different sources of energy used.

Table 13 EEG databases for building materials

Database	**Geographical Boundary**	**Unit**	**Coverage**	**Primary data source**	**Lifecycle boundary**	**Method**	**Standardization**
3EID (EG and Emission Intensity Data)	Japan	TOE or Ton-C/ ¥	EEG	Japanese Economic Input-Output data	Cradle to gate	Input-Output	N/A
ICE	UK/Europe	$kgCO_{2eq}$/SI unit (kg, m^2 etc)	EEG	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, m^2 etc)	LCI	Industry	Cradle to gate	Process	N/A
Carnegie Mellon EIO LCA	N.A. (US)	t-CO_2/$US	LCI/EG	US Economic IO data	Cradle to gate	Input-Output	N/A
US EG	N.A. (US)	Lbs CO_2/ft^2	EEG	Athena data	Cradle to grave	Process	N/A
FWPA	Australia	CO_{2eq}/SI unit (kg, m^2 etc)	EG	Ecoinvent	Cradle to gate	Process	ISO 14040/14048
BPLCI (Building Product LCI)	Australia	Emission/SI unit (kg, m^2 etc)	LCI	Ecoinvent	Cradle to gate	Process	ISO14044
NZ EE/EG data	New Zealand	$	EEG	New Zealand Economic IO data	Cradle to gate	Input-Output	N/A
Ökobau.dat	Germany	Emission/SI unit (kg, m^2 etc)	LCI/A	Gabi database	Cradle to gate	Process	EN15804
ecoinvent data 2.2+	Switzerland	Energy resource/SI unit; Emission/SI unit (kg, m^2 etc)	LCI (unit process and cradle to gate), LCIA/EEG	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, m^2 etc)	LCA/EEG	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, m^2 etc)	LCI	Ecoinvent	Cradle to gate	Process	N/A

EE: Embodied Energy, EG: Embodied GHG, EEG: Embodied Energy and GHG, LCI: Life cycle inventory

BOX 2 Data consideration of EEG emissions

The main requirements for EEG data are as follows;

- Materiality: EEG data should cover the most important construction materials, building services, energy carriers, transport services and waste management processes
- Consistency: EEG data must rely on the same methodological approach, using the same system boundary definitions and using the same background data.
- Transparency: EEG data should provide the fullest possible transparency, enabling tracking back to the smallest unit of information (unit process data) and proper citation of the information sources used
- Timeliness: EEG data should be reasonably up to date. Their age may differ depending on the innovation cycles in the respective industries.
- Reliability: EEG data should be based on sources and information considered reliable and true.
- Data quality: EEG data should be systematically and independently checked regarding their quality

4.7 Guidelines and standards related to EEG emissions in construction

A list of general and construction-specific EE or EG calculation standards and guidelines is presented in Table 14. It shows the full reference title and year of publication (or release), the basic definition and included scope of emissions, methodology basis, geographical boundary (or scope of geographic applicability), and some comments on perceived “limitations” as they relate to the specific application and decision-making contexts in the building and construction sector.

Table 14 Standardisation for EEG and/or LCA

Organisation	Reference	Year	Definition	Unit*	Target	Emission scope	Methodology	GHG quantification methodology	Geographical boundary	Note
ISO	ISO 14067: Carbon footprint of products	2012	GHG emissions of a product system	CO_{2eq}	Product (general)	Scope 1, 2 & 3	LCA (ISO 14040s)	IPCC (100 yrs time horizon)	World	- Not exclusively targeted to buildings
ISO	ISO 21930: Sustainability in building construction: Environmental declaration of building products	2007	Environmental impacts (declaration) of building products	various	Building product	Scope 1, 2 & 3	LCA (ISO 14040s)	IPCC (100 yrs time horizon)	World	
UNEP	UNEP-Common Carbon Metric	2010	GHG emissions from building operations	MJ & CO_{2eq}	Building	Scope 1 & 2	Process	IPCC (100 yrs time horizon)	World	- Focus on the operational stage only.
WRI & WBCSD	GHG Protocol Product Accounting & reporting standard	2010	GHG emissions caused by product's life cycle stage	CO_{2eq}	Product (general)	Scope 1, 2 & 3	LCA	IPCC (100 yrs time horizon)	World	- Not focused on building/building material - general products for carbon footprint using LCA
CEN	CEN TC350: EN15978 - Sustainability of construction works-assessment of environmental performance of buildings-calculation method	2009	Environmental impacts (including GHG emissions) through the life cycle of building	various	Building	Scope 1, 2 & 3	LCA	IPCC (100 yrs time horizon)	Europe	- Not specific embodied GHG. Just all LCA impacts are defined here as embodied impacts
CEN	CEN TC350 EN15804, Sustainability of construction works - Environmental product declarations - product category rules	2008	Environmental impacts (including GHG emissions) through the life cycle of product	various	Product	Scope 1, 2 & 3	LCA	IPCC (100 yrs time horizon)	Europe	- Not specific embodied GHG. Just all LCA impacts are defined here as embodied impacts
PAS	PAS 2050	2011	GHG emissions caused by a particular activity or entity, and thus a way for organisations and individuals to assess their contribution to climate change	CO_{2eq}	Product (goods & services)	Scope 1, 2 & 3	LCA (process based)	IPCC (100 yrs time horizon)	Europe (particularly UK)	- Not exclusively targeted to buildings
RICS (Royal Institution of Chartered Surveyors)	RICS - Methodology for the calculation of EG as part of the life cycle carbon emissions for a building	2012	Carbon emissions associated with energy consumption and chemical processes during the manufacture, transportation, assembly, replacements and deconstruction of construction material or products	CO_{2eq}	Building	Scope 1, 2 & 3	LCA	IPCC (100 yrs time horizon)	Europe (particularly UK)	Used ICE (Inventory of Car bon & Energy) data
BSRIA	BSRIA (Building Services Research & Information Association)- Inventory of Carbon & Energy (ICE) summary guide	2011	Sum of fuel related carbon emissions (i.e., EG which is combusted but not the feedstock energy) and process related carbon emissions (i.e., non-fuel related emissions which may arise from chemical reactions) associated with a product or service and within the boundaries of cradle-to-gate.	MJ & CO_{2eq}	Building materials	Scope 1, 2 & 3	Process LCA	IPCC (100 yrs time horizon)	Europe (particularly UK)	

* Unit is only concerned for energy and GHG emissions.

Table 14 Standardisation for EEG and/or LCA (Continued)

Organisation	Reference	Year	Definition	Unit*	Target	Emission scope	Methodology	GHG quantification methodology	Geographical boundary	Note
UK CPA	UK CPA (Construction Products Association) - Guide to understanding the embodied impacts of construction products	2012	Carbon Dioxide (CO2) or greenhouse gas (GHG) emissions associated with the manufacture and use of a product or service.	MJ & CO_{2eq}	Building products	Scope 1, 2 & 3	LCA	Kyoto protocol (6 major gases)	UK	- Not specific EG. Just all LCA impacts are defined here as embodied impacts
Carbon Trust	Carbon footprinting: Footprint measurement	2010	Total GHG emissions caused directly and indirectly by an individual, organisation, event or product.	CO_{2eq}	Product (general)	Scope 1, 2 & 3	Process LCA	Kyoto protocol (6 major gases)	UK	- Not speicified carbon intensity data
FWPA	Development of an Embodied CO2 emissions module for AccuRate	2010	Total GHG emissions caused from resource extraction, transportation, manufacturing and fabrication of a product or system (cradle-to-factory gate).	MJ & CO_{2eq}	Building materials	Scope 1, 2 & 3	Process LCA	IPCC (100 yrs time horizon)	Australia	- Cradle-to-gate boundary (but linking to building with out consideration of life span of components)
SEI	Development of an embedded carbon emissions indicator	2008	Not speciifed but uses general definition	MJ & CO_{2eq}	Product	Scope 1, 2 & 3	Input-output analysis	IPCC (100 yrs time horizon)	UK	
PEF	Product Environmental Footprint	2013	Sum of GHG emissions and removals in a product system							
KBOB	KBOB recommendation 2009/1:2014	2014	GHG emissions of production and disposal of construction materials and building technologies	CO_{2eq}, MJ oil eq	building materials etc.	Scope 1, 2 & 3	Process LCA	IPCC 2013, CED (harvested energy)	Switzerland	
SIA	SIA 2032	2010	Grey energy of buildings	CO_{2eq}, MJ oil eq	Building	Scope 1, 2 & 3	Process LCA	IPCC 2013, CED (harvested energy)	Switzerland	
SIA	SIA 2040	2008	SIA energy efficiency path	CO_{2eq}, MJ oil eq	Building	Scope 1, 2 & 3	Process LCA	IPCC 2013, CED (harvested energy)	Switzerland	

* Unit is only concerned for energy and GHG emissions.

5. EEG evaluation Applications

5.1 Overview of context-based applications

As previously noted, the range of uses or applications of embodied impacts data in building and construction are varied and diverse because of the diverse group of stakeholders or actors, who in turn have different purposes (and decision making contexts) for needing or using EE and/or EG emissions data (Balouktsi et al. 2015; 2016). An overview of these concerns and contexts for four stakeholder types was discussed in section 2.3.

In this chapter, three application areas are presented:

- Building design
- Manufacturing and recycling process
- Policy impact

Material selection is one of the key aspects of building design. Through the efficient use of material in a building design stage, we can reduce energy and GHG emission of building. The next section describes the calculation of EEG in the building design stage. Also, we compare the embodied impacts of key building materials, for typical residential buildings (detached) in different countries. Total EEG can vary depending on the service life of the building element. As Raulf and Crawford (2013) argued in their study, EE, particularly recurring EE, which is repeated during the life span of building, is highly dependent on the service life of the building product or element.

This chapter also discusses other issues which may be considered in the EEG of buildings, if relevant. Fluorinated gas usage as feedstock (manufacturing of insulation material) or coolant leakage from cooling systems in the buildings are a typical examples influencing GWP of buildings, which is not based on fossil fuel consumption and often ignored in the quantification of EG. Also, energy or GHG emissions from construction sites and transportation between manufacturing sites are ignored either due to difficulties of quantification or because of their insignificance. These issues, which may influence the EEG of a building (e.g., non-fuel based GHG emissions such as f-gas from insulation and cooling systems, energy or GHG emissions from transportation waste management, onsite emissions, recycle/reuse of material and credit of steel etc.) are discussed.

Finally, the last section aims to understand the values of EEG for building and civil engineering construction in individual countries and to identify the research objective of Annex 57 in a quantitative manner. Generally, the calculation of EEG for buildings involves the multiplication of the EEG in a database for a given unit of individual materials (e.g. MJ/t, kg-CO_2/t) and the quantities used (e.g., tonne, m^3 etc.). The last section provides a method for calculating EG of the construction sector in individual countries according to the IO analysis approach.

5.2 Building design application

Building designers can reduce energy and GHG emissions by changing their building plans and specifications. This section describes simple approach quantifying the embodied impacts (energy and GHG emissions) in the early design stage of a building.

Table 15 Materials and equipment for simple calculation

Element/materials/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(polystyrene or urethane foam)	Weight (t)	The estimate value of the weight of the insulation (polystyrene or urethane foam)
		Fluorocarbon gases contained the above insulation	Weight (kg)	Amount of fluorocarbon gas 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. The items which are not included in the above such as wood products, bricks and so on are included in this item..
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.
	Freon Gases		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 include temporary work, electricity bill and waterworks charge.

5.2.1 Streamlined approach of embodied impacts quantification

In a building planning stage, it would be possible to identify equipment and materials which contribute to EE or EG reduction in the building. The EE or EG can be calculated based on the materials and equipment by pinpointing in the building construction where a great deal of energy consumption or GHG emissions occur. Even in the basic design stage, when the building structure is determined, quantities of materials such as concrete, steel bars and steel frames could be quantified. In terms of facilities, the type of heat source/capacity and air-conditioner capacity in the HVAC 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. Table 15 shows some of the key materials and equipment based on the building work or elements. In this case, the embodied impacts can be simply quantified using the existing impact intensity dataset for building products/elements and equipment. Depending on the building work, it can be more detailed.

The initial embodied impacts quantification (cradle to construction site), while the whole embodied impacts over the life cycle, EE or EG intensity can be obtained using the existing database, which is developed by either process based LCA, IO based or hybrid approach.

Fluorocarbon may release either from wall insulation material or leakage from refrigerant and end of life of buildings. In this case, fluorocarbon release can be estimated multiplying the fluorocarbon gas by corresponding GWP. For example, the amount of fluorocarbon gas contained in the insulation materials, it can be estimated using the percentage of fluorocarbon gas content in major insulators. Also, the fluorocarbon gas which contained in a refrigerant in cooling system. This example quantification is shown Appendix E (Table D1~D5), which gives an indication of the percentage of the refrigerant content in refrigerators and air-conditioners. Thus, we can estimate GHG emissions due to fluorocarbon gas leakage from the insulation or refrigerators using the leakage (2~15% for chillers or 1~10% for air-conditioners as shown Appendix E) and recovery factors when disposed. The GWP of fluorocarbon gases which used for refrigerator (Table E5 in Appendix E).

5.2.2 Example of quantification of EEG

An example building is used to illustrate how to quantify the EEG in the building design stage.

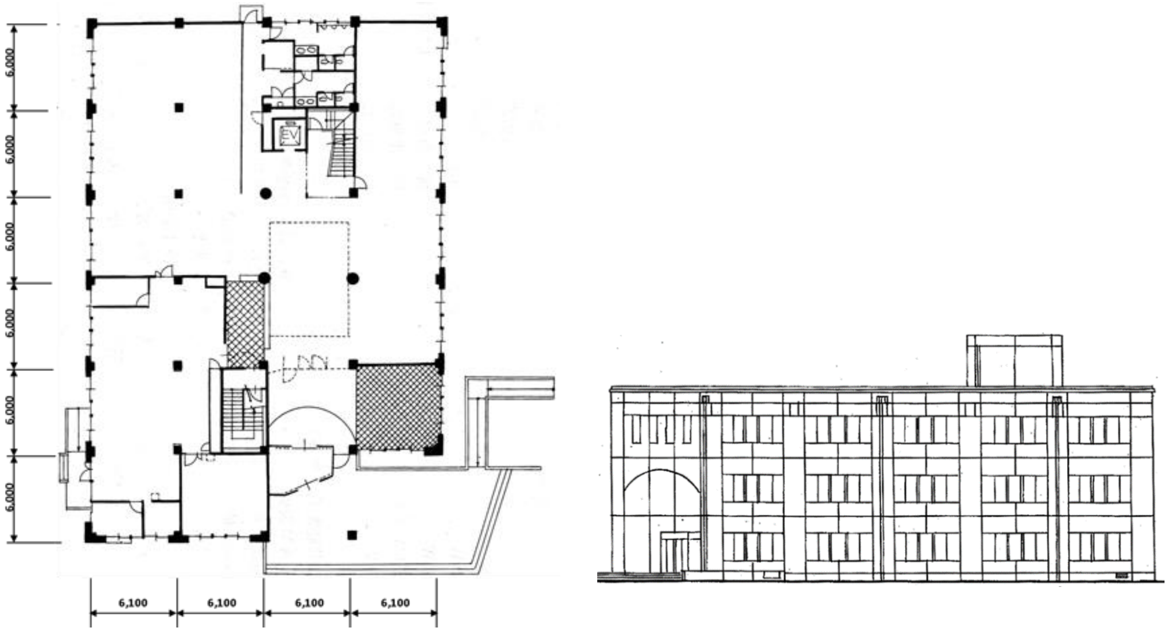
5.2.2.1 Description of example building

To show the quantification approaches in the design stage, a 3-storey reinforced concrete building is selected as an example. The specification of this example building is represented in Table 16 and Figure 14 shows the plan of this building.

Table 16 Outline specification of example building

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 heat-pump-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.

Source: (BCI, 2004)



(a) Ground floor layout (BCI, 2004) (b) East front view (BCI, 2004)

Figure 14 Example building layout and view

5.2.2.2 Preparing embodied impact intensities for example building

The IO based database is used in in this sample calculation. EEG 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 detail calculation results of 2 types of sample buildings (See for preparing intensities of example building in Appendix F).

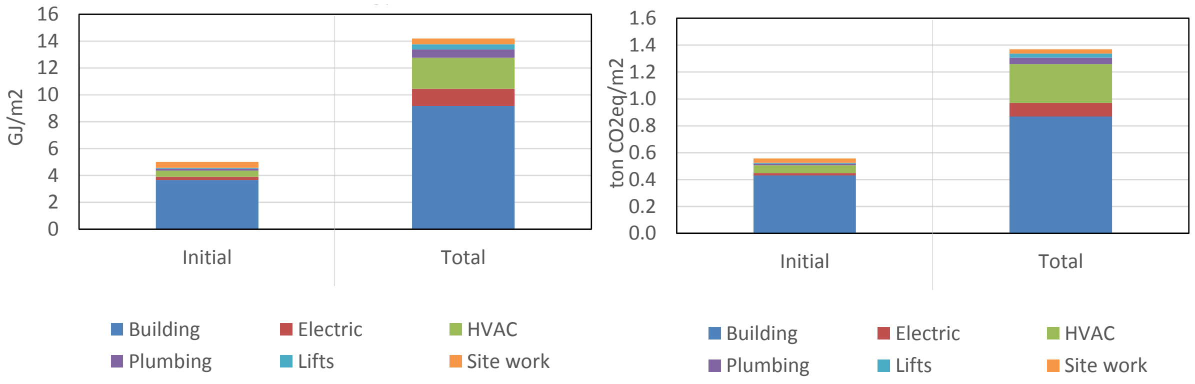
5.2.2.3 Results of embodied impacts of example building

The streamlined quantification results are shown in Figure 15 and its calculation sheet is illustrated in Table G1 and Table G2 in Appendix G for initial embodied and total embodied impacts over the life cycle of example building. As seen in Figure 15 (a), the initial EE (cradle to construction site) is 4.99GJ/m^2. Total EE over the life cycle (60 years lifetime) is 9.75 GJ/m^2, which is 1.95 times more than the initial EE. Of the elements, 'Electric' had the greatest increase from initial to total EE, increasing from 0.24 to 0.77GJ/m^2, which is a 3.2 times increase. Total EE results for HVAC and lifts were also much greater than initial, as much as 3 times however, 'Building', as the volume based increase, went from 3.67 GJ/m^2 initial to 9.17 GJ/m^2 total. This was due to replacement of internal finishes, which contributes 40% of total life cycle EE.

For EG shown in Figure 15 (b), the initial EG is 0.56 ton-CO$_{2eq}$/m^2. Over the life cycle, total EG is 0.97ton-CO$_{2eq}$/m^2, which is 1.7 times more than the initial EG. Similar to EE, 'Building' and "HVAC' are large contributors to total EG, 85% (68% for 'Building' and 17% for 'HVAC). This contribution includes release of Fruorocarbon gases from insulation material and leakage from the HVAC system (0.06 ton-CO$_{2eq}$/m^2), which is 6% equivalent of total EG.

The results throughout the streamlined approach is compared with detailed results. Yokoyama et al. (2016) quantified the EEG for the same building using the IO approach based on the detailed bill of quantify for the example building. According to them, total EE for the same building is shown

12,568,761MJ which is only 3% more than streamlined approach (12,177,252MJ). On the other hand, total EG of the example building is appeared 5% less comparing to detailed approach (1,367,120kg-CO_{2eq}).



(a)Embodied energy(EE)

(b) Embodied GHG(EG)

Figure 15 Embodied impacts of example building

5.3 Quantity of materials used in building

A number of materials are required for building construction. Some materials, such as concrete, timber, steel etc., are a very high proportion of the total mass of the building. To manage EEG, it is important to understand the key building materials that are required in building construction.

5.3.1 Examples (detached houses) in different countries

Material consumption for detached houses are compared between four different countries (Australia, Canada, Norway and UK). For comparison of the material usage, a typical detached house from each country is selected from the literature. Brief information for the selected buildings from each country is shown in Table 17.

Table 17 Brief summary of detached houses in different countries

Country	Building type	Location	Storey	Floor area (m^2)	Life span	Bill of Quantity (BoQ) data	Reference
Australia	Timber framed brick veneer with concrete slab	Melbourne	Single	82	50	Estimated based on Australian standard	Fay (1999)
Canada	Timber framed brick wall with concrete slab	Vancouver	Double	236*	60	Extracted from a typical house built from 1980	Zhang et al (2014)
Norway	Timber framed concrete floor	Stored	Double	187	50	Based on Norwegian standard house, TEK07 house standard from 2007)	Dahlstrøm (2011)
UK	Traditional masonry wall (brick & block)	Nationwide	Single	130	50	New building. Assumption based on UK typical residential buildings	Franca (2012)

*Included garage

Detached house in Australia

Brick veneer single storey detached housing construction is very common in Australia. As a typical dwelling type, a single storey dwelling which has 96 m^2 of habitable area is selected as the typical Australian residential building in this case. It comprises a living area, kitchen/family area, three bedrooms, laundry, bathroom and toilet. The area of windows is 36% of the total floor area. The typical Australian house has a concrete floor, timber framed brick veneer external walls and a concrete tiled roof. The floor plan for the typical Australian house is shown in Appendix H (Figure H1).

Canadian detached house

Zhang et al. (2014) performed LCA analysis of a typical single family residential building in Canada. The typical Canadian house is a double storey dwelling located in Vancouver. The building has a floor area of 236 m^2 including the garage, refer Appendix H (Figure H2). The building has two living areas, two bedrooms and two bathrooms, a kitchen and a garage on the ground floor and two bedrooms, two bathrooms, a kitchen, three living areas and balcony on the second floor. The building has timber framed brick external walls with concrete slab on ground and aluminium framed windows. The bill of quantities for this building was taken from the literature (Zhang et al., 2014).

Norwegian detached house

For the typical Norwegian house, the datais taken from Dahlstrøm (2011)'s study, which assessed the environmental costs and benefits of moving to the passive house standard compared to the current dwelling standard (TEK07/TEK10). The typical Norwegian family residence is located in Stored, Western Norway.

The Norwegian house is a double storey construction, timber framed and timber clad, with a concrete slab on ground having a total floor area of 187 m^2, refer Appendix H (Figure H3). Due to the weather conditions in Norway, the building has an insulated ground floor, outer doors, ceiling etc.

The bill of quantifies was taken from the literature (Dahlstrøm, 2011).

Detached house in UK

The typical detached house in the UK was selected from the literature (Franca, 2012). The typical UK house is a double storey residential building of brick and block construction with 4 bedrooms having a total floor area of 130 m^2. The bill of quantities was taken from the literature (Franca, 2012). The floor plan for typical detached house in the UK is shown in Appendix H (Figure H4).

5.3.2 Key material comparison between countries

Figure 16 shows material input (%) by key elements of the buildings. The substructure and wall elements are generally dominant components in the mass of the buildings, representing 93% for Australia (61% for substructure, 32% for wall), 77% for Norway (54% for substructure and 23% for wall), 73% for Canada (37% for wall and 36% for substructure), and 80% for UK (59% for wall and 21% for substructure). For Canada, the walls are slightly heavier than substructure. This is because the Canadian building consumes more plaster for the wall elements than the other countries. The mass of the UK house is dominated by the masonry (brick/block) wall.

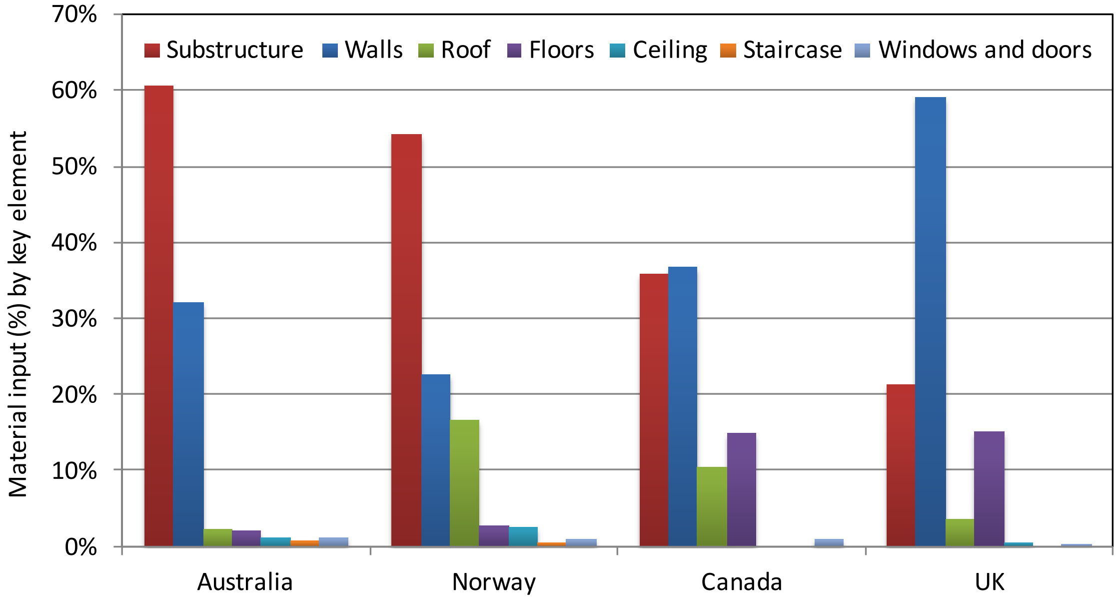


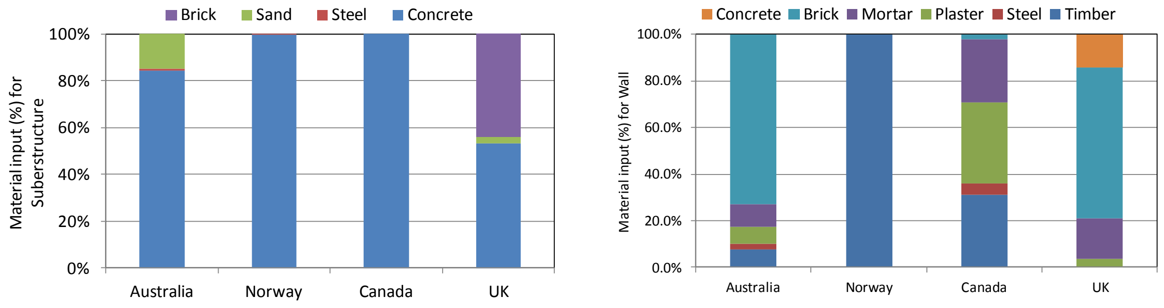
Figure 16 Material input (%) by mass of element of residential building

For the key elements, material input, EEG are compared in the Figure 17. For timber- wall framed houses, the substructure is almost exclusively composed of concrete, refer Figure 17 (a). Even for the masonry walled houses (UK), the substructure is mainly composed of concrete and completed with brick.

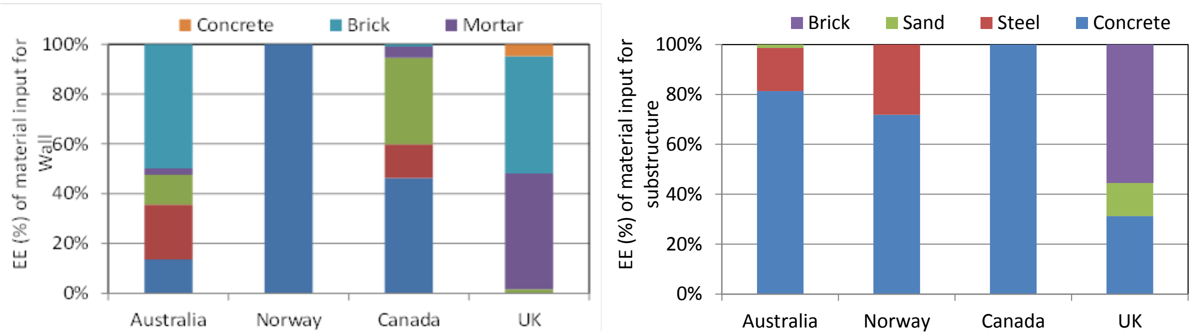
There is no obvious pattern in wall element mass breakdowns due to the great variation in wall construction methods and materials.

For the Australian house, external walls are timber-framed, clad with brick veneer outside and with plaster board inside. Internal walls are timber framed and covered with plasterboard. On the other hand, walls of the Norwegian house are completely made of timber, including frame, external cladding and internal lining. The Canadian house walls, external and internal, are timber-framed. Plaster is used to clad for internal faces of the walls and OSB for the external faces. Also brick veneer is used to clad the outside of external walls on the ground floor and mortar is used to clad the outside of external walls on the first floor. The British house is a typical masonry house, therefore walls are only made of concrete, bricks, mortar (for fixing the bricks) and plaster (for internal lining).

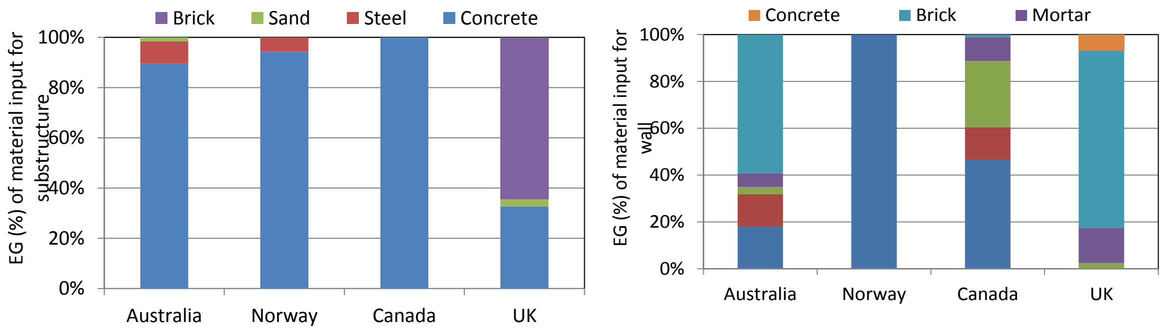
The EEG data might be different depending on the different countries and quantification methods. In this comparison, most of countries used ICE data base (Hammond and Jones, 2008, originally taken from each of the case building references) for EEG except for Australian case, which is derived from IO based analysis (Treloar, 1998 Taken from Fay (1999)). Thus, there might exist the variation of EEG for the building products due to the different quantification methodology and geographical boundary between countries, however, the pattern for EEG for the substructure and walls (Figure 17 (c) and (d)) shows similar to that of the material inputs (Figure 17 (a) and (b)). However, interestingly, steel only contributes less than 1% for substructure and 3% to 5% for wall as mass based, but EE shows much higher contribution as 17% to 28% for substructure ((c) in Figure 17) and 14% to 22% for wall elements ((d) in Figure 17). This is because of unit intensity of steel is much higher than other building materials. EG for steel shows similar results as 6% to 9% for substructure and 14% for wall elements ((e) and (f) in Figure 17).



(a) Material input (%) for substructure (b) Material input (%) for wall



(c) EE of material input for substructdure (d) EE of material input for wall



(e) EG of material input for substructure (f) EG of material input for wall

Figure 17 EEG of material for dominant elements (Substructure and Wall)

5.4 Service life of building component

5.4.1 Service life of building component

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

In relation to recurrent embodied impacts, several studies (Cole and Kernan, 1996; Crawford et al., 2010; Fay et al., 2000; Rauf and Crawford, 2014; Treloar et al.2000) analysed its importance. For example, Treloar et al. (2000) shows that recurrent EE is 32% of the initial EE of residential buildings over a 30-year life span. Crawford et al. (2010) analysed life cycle energy for different types of residential buildings. According to their study, recurrent EE has a broad variation from 7% to 116% of initial EE. For office buildings, Cole and Kernan (1996) reported that recurrent EE, comprising finishing, servicing and envelope maintenance, was 128% (6.56 GJ/m^2), 135% (6.45 GJ/m^2), and 139% (6.32 GJ/m^2) of the initial EE of steel, concrete and timber over a 50 years life span. Fay et al (2000) analysed how recurrent EE influenced the total life cycle energy for different life spans of residential buildings. These references emphasized the importance of recurring embodied impacts, which contribute high proportion of total, even though they may have very different situations and aspects. The share of recurring EE relative to initial EE for different building types are represented in Table I1 (Appendix I).

5.4.2 Effect of EE with different service life (example)

To demonstrate how service life influences the EE of a detached residential building, the Australian house from the previous section has been selected as an example. Material requirements are taken from literature (Fay, 1999). Building material (mass base) by key elements is given in Figure 18.

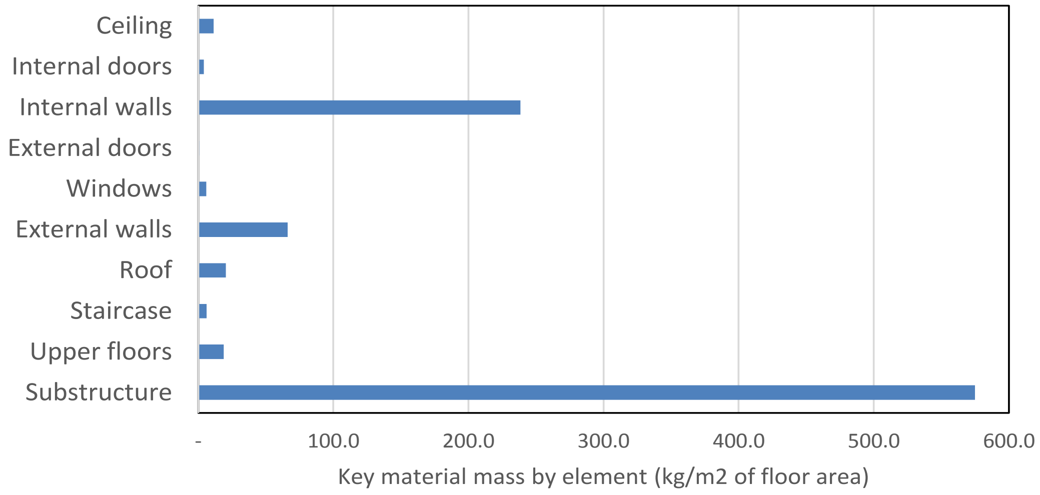


Figure 18 Material mass by key building elements (kg/m^2 of floor area)

For the example building, EE (initial and recurring) are quantified using the material requirements and EE coefficient data, which were developed using the Australasian LCI (Version 2013.12) and the BP LCI database for Australia. Service life of building components were obtained from the literature as shown in Table 18.

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Table 18 Service life for selected building components

Component	Minimum service life (Min), years	Average service life (Mean) ,years	Maximum service life (Max) , years
Concrete roof tiles*	30	40	50
Cement brick*	Lifetime++	Lifetime	Lifetime
Plasterboard*	20	35	75
Paint*	5	10	15
Aluminum framed window*	15	25	40
Timber weatherboard*	15	20	25
Timber framed window*	20	25	30
Shingles**	10	15	20
Ductwork**	15	58+	100
Brick tiles**	25	63+	100
Galvanized steel (marine)***	10	13+	15
Galvanized steel (mild weather)***	30	40+	50

* Rauf and Crawford (2013)
** Building Green (2009)
*** CRC CI (2006)
\+ average value for minimum and maximum
++duration of building's life

Figure 19 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.

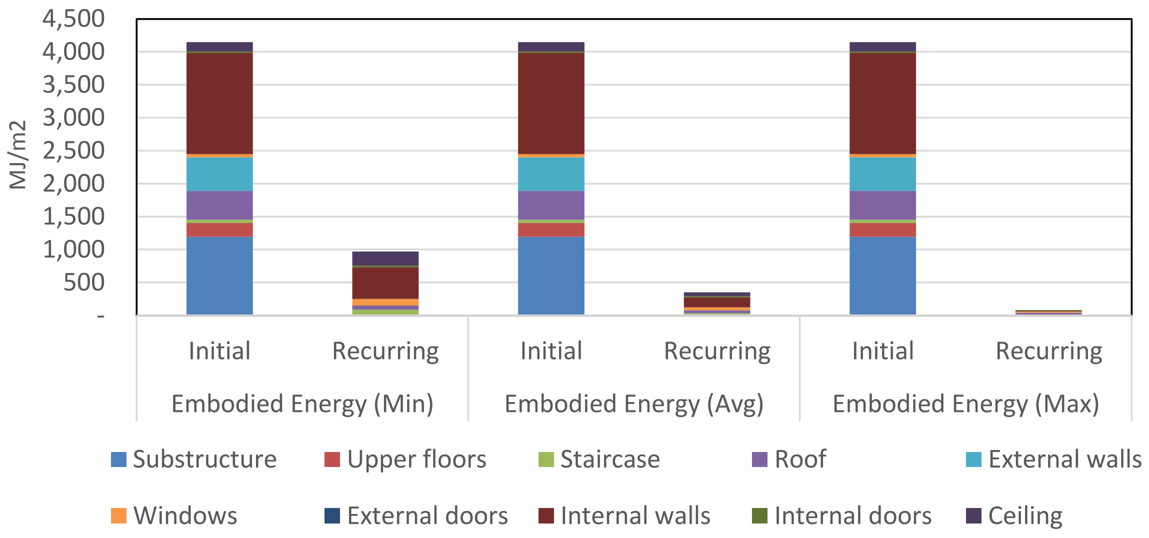


Figure 19 EE of residential building (50 years life span)

5.5 Influence of GHGs other than CO_2 (insulation and refrigerator)

In the EG quantification of buildings, we normally consider a number of GHGs including carbon dioxide (CO_2), methane (CH_4), fluorocarbon, etc. However, there are some emissions which may be ignored or missed in the quantification, such as fluorocarbons from insulation material or leaking from cooling systems in buildings (e.g., HCFCs). This section focuses on these emissions and describes how these influence the EG emissions of buildings.

5.5.1 Fluorinated gas (fluorocarbons)

There are four different types of fluorinated gases:

- Hydrofluorocarbon (HFCs)
- Perfluorocarbons (PFCs)
- Sulphur hexafluoride (SF_6) and
- Nitrogen trifluoride (NF_3).

Of these, HFCs have the greatest influence on GWP from buildings. Due to the Montreal protocol, Freon gases (CFCs) have been banned from the industry and HFCs, as an alternative to CFCs, have been used in buildings in such applications as a blowing agent for 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.

5.5.1.1 Fluorocarbon release from insulation materials

Current status of fluorocarbons in insulation materials

According to S EPA (2011), HFC consumption for the building products is estimated to be 38 million tonnes of CO2eq globally in 2010. Most of this consumption (98% of total) is in developed countries, particularly for insulation materials (51% for spray and 24% for XPS board).

Not all current existing EG data considers these emissions. Due to the GHG emission phase of the product (Insulation materials which contain XPS (extruded polystyrene) or SPF (spray polyurethane foams), release a great deal of GHG in the use phase), these emissions are not included in the EG data for the building material. This issue has been discussed in the IEA Annex 57. Most of the EG data for the building materials are limited to the initial EG (cradle to gate or site) or recurring EG boundary. For these materials emissions occurring during the operational phase (even though it is not due to energy consumption during the use phase) should be considered in EG. Existing life cycle GHG or EG for buildings tend to miss or ignore the GHG emissions from the use phase of insulation materials, which contain XPS or SPF.

In non-Article 5 countries (mainly developed countries), transition to HFC-134a, HFC245fa, and others is under way and, in Europe and Japan, more fluorocarbon-free options (such as HCs) are also included. In Article 5 countries, it is expected that demand for use of insulation materials will grow in the future.

Release of fluorocarbon gases

Fluorocarbon gases contained in insulation materials are released into the atmosphere over time and, depending upon the type, sometimes almost completely in two decades or more (JTCCM, 2006). In addition, a change in thermal performance due to the release of fluorocarbon gases takes place decreasing the insulation performance, thereby possibly leading to an increase in air-conditioning energy (Yamamoto et al., 2015 (originally referred from NEDO, 1999)).

Quantification of fluorocarbon release from insulation materials

The amount of fluorocarbon gases released from insulation materials is calculated using the following equation, on the assumption that they are all eventually released into the atmosphere.

$$\mathrm{Release}_{\mathrm{HFCs}} = A \cdot d \cdot \rho \cdot f \cdot GWP$$

where
$Release_{HFCs}$: Fluorocarbon release from insulation materials (kg-CO_{2eq}),
A: Insulation material area (m^2),
d: Insulation material thickness (m),
ρ: Heat insulation material density (kg/m^3),
f: Initial content rate of fluorocarbon gases (wt%),
GWP: Global Warming Potential

5.5.1.2 Fluorocarbon leaks from refrigerators

Concerning insulation material's foaming agents and refrigerants for air conditioning systems, ordinary specifications and low environmental load-compatible specifications are compared for the same building.

Current status

In developed countries, R410A and R407C are mainly used for air-conditioning and R404A for refrigeration. In developing countries, R22 is mainly used. In developed countries, CFC has been categorically prohibited and HCFC will also be totally banned in 2020 at the latest. In developing countries, CFC's were prohibited in 2010 and HCFC will also be totally banned by 2030.

Under such circumstances, refrigerants for refrigerators are being developed for the transition to low-GWP materials (including R32 and R1234Ze). The current trends of uses for refrigerants (UNEP, 2015) are represented in Appendix J (Table J1).

Fluorocarbon leakage

In general, the amount of Fruorocarbon gases used in compression refrigerators are 1 kg per 3 kW of refrigerator heat output and therefore, after deciding which refrigerators are installed, their effects can be added as EG. However, as Fruorocarbon gases may be emitted from the refrigerator as fugitive gases over time, it is necessary to estimate these fugitive losses, which, are equivalent to the amounts of Freon gases used for refills. Generally speaking, 1-35% of the Fruorocarbon gases installed in the refrigerator (Table 19) can be considered to be an annual fugitive loss and the actual amount largely varies depending on refrigerator model and maintenance method. When an old refrigerator is replaced by a new model, the recovery rate of Fruorocarbon gases from the old refrigerator is estimated to be approximately 30%, thus releasing 70% into the air (Table 19).

HFCs, used as coolants in refrigerators, are released into the atmosphere due to leaks from cooling systems (i.e., piping) during operation and improper recovery from the end of life stage of system. The ratio of coolant leaks may vary depending on the execution quality and controlled state but it is normally reported to be 2%-15% for chillers, 10%-35% for medium & large commercial refrigeration and 1%-10% for residential and commercial A/C, including heat pumps (IPCC, 2006). The recovery rate of coolants at the disposal stage, which can vary widely country to country, is reported to be 0%-95% (IPCC, 2006). Regarding the ratio of leaks and recovery rate of coolants, Table 19 represents IPCC Guideline values for leakage rates (Table 19 is for the Japanese case (Japanese Gov., 2009; 2013).

Table 19 Emission factor and collection rate at the time of disposal of refrigerator

Sub-application	Emission factor+		Recovery efficiency
	IPCC Guideline (2006)	Japan1*	Japan**
Chillers	2%-15%	6%-7%	30%
Medium and large commercial refrigeration	10%-35%	12%-17%	
Residential and commercial A/C including heat pump	1%-10%	2%-5%	

*1 Including refrigerants collected at the time of maintenance and emissions due to accidents and equipment failures
* METI, (2009) ** METI (2012)
+ Coolant (refrigerant) emission factor

Except for developed countries, certain types of insulants contain Fruorocarbon gases as foaming agents. Their consumption is prominent especially in developing countries with a high demand for construction. The Fruorocarbon gases in insulants usually dissipate within a few years and it is reasonable to conclude that Fruorocarbon gases take no part in improving insulation performance. Their amount in foamed insulants is determined based on Table K1 in Appendix K.

Quantification of coolants leakage

Coolant leakage can be calculated using the following equation (IPCC, 2006):

$$Leak_{HFCs} = \left\{ (V \cdot k \cdot t) + V \cdot \left(1 - k_d \big/ 100 \right) \right\} \cdot GWP$$

$$V = V_0 \cdot C_0$$

Where,

$Leak_{HFCs}$: HFCs leakage (kg-CO_{2eq})
V: Initial amount of coolant filled (kg],
V_0: Amount of coolants sealed in (kg/kW),
C_0: Refrigerator capacity (kW),
k: Emission factor of leaks from refrigerants in operation (%/year),
k_d: Recovery rate at the time of disposal (%),
t: Number of years operated (year), and
GWP: Global Warming Potential

To illustrate the effect of fluorocarbon release and leakage, an example building is selected. This example building is a multi-complex building, which has 7,420 m^2 of total floor area with retail and office spaces. For the quantification of fluorocarbon leakage from this building, a simple calculation is used based on 2005 Japanese Input-Output Analysis.

Table 20 describes the outline of the example building. The air conditioner's capacity and number of conditioner units are shown in Table K4 (Appendix K). Specifications for heat insulation material are shown in Table K5 (Appendix K), and construction costs in Table K6 (Appendix K).

Table 20 Outline of the sample building

Intended use	**Office**
Location	Japan
Structure	Steel, (Steel Reinforced-concrete partly）
No. of stories	8 stories, 1 basement
Site Area	831 m^2
Gross floor area	7,420 m^2
Electrical equipment	Receiving high-voltage electricity: 1400kVA, Lighting and consents, Broadcast and telephone equipment, Disaster prevention system
Air-conditioning equipment	Air cooled heat pump air conditioner (multi type and single type), Total heat exchanger
Water supply and drainage sanitation	System for direct connection to water supply, Sanitary facilities, City gas equipment
Elevator facilities	1000kg x 2 units, 1150kg x 1 unit.

Source: CRI (2004)

Results of release and leakage of fluorocarbon gases from example building

Initial EG are 0.65 ton-CO$_{2eq}$ from cradle to construction site when fluorocarbons release and leaks are not considered from the insulation material and building. On the other hand, when they were considered, EG increased 10% to 0.71 ton-CO$_{2eq}$ per m^2 of building. When considered the EG during the life cycle of building (60 years in this case), the emissions were much higher. As shown in Figure 20, total EG were 1.30 ton-CO$_{2eq}$ per m^2 when fluorocarbons emissions are not considered (w/o fluorocarbons in Figure 20). When considering these emissions (w/ fluorocarbons in Figure 20), the total EG increased 41% to 1.84 ton-CO$_{2eq}$/m^2). This is due to the contribution of CFCs leaks (0.41 ton-CO$_{2eq}$/m^2) from the 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 EG can vary depending on the fluorocarbons consideration. Many existing EG studies for buildings ignore the GHG release/leakage emissions or assume it to be negligible. However, these GHG emissions, as shown in this example, are not small. These emissions should be taken into account for embodied or life cycle GHG emissions of buildings.

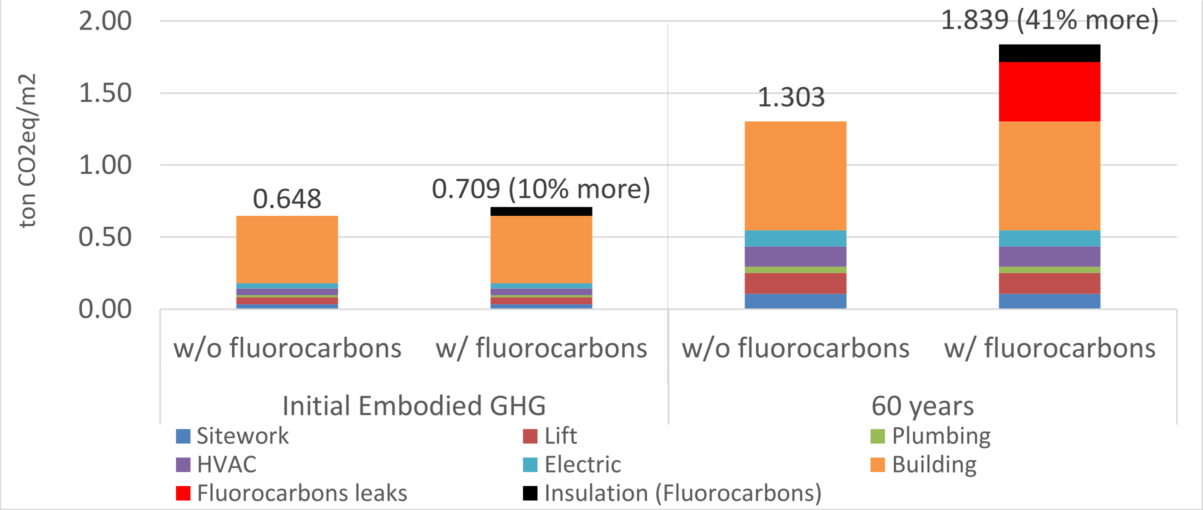


Figure 20 EG of the example building

5.6 Consideration of Materials and Systems

5.6.1 Recycled or reused material

To reduce energy consumption or GHG emissions, it is recommended to use more recycled or reused materials for building construction. The energy required to process most virgin materials is greater than that required to process recycled materials. For materials such as virgin (primary) aluminium, the EG is much higher than that of recycled materials as much more energy is used in the extraction process from ore than in the recycling process.

Figure 21 shows an example for aluminium windows. To manufacture a 1 m^2 window with primary aluminium material, 43.4 kg-CO_{2eq} is emitted. To reduce the GHG emissions, various recycled aluminium products can be considered for the window from 10% to 30%. Depending on the recycled proportion, total EG also varies proportionally. This is not only the case for aluminium products but also for other building materials or components, such as concrete, steel, timber etc. Due to efficiency of material usage in building construction, the recycled and/or reused portion are continuously increasing.

In the preliminary survey for EEG of recycled (reused) material (see Appendix C), only a few countries such as Switzerland consider recycled or reused materials for their analysis. However, there may not always be available data for recycled/reused materials. Thus, it should be clarified whether this has been taken into account in any quantification study.

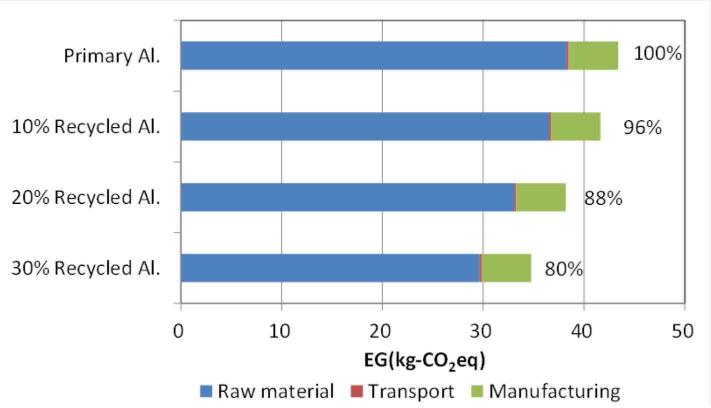


Figure 21 EG comparison between different recycled aluminium for windows

For quantification of EG from steel, the World Steel Association (WSA, 2011) proposes a methodology based on the End of Life (EoL) approach. This approach assumed that steel products are suitable for horizontal recycling, and thus GHG emissions due to manufacture of steel are redistributed to the next-generation product, thereby levelling the environmental impact (GHG) imposed at the production stage. That is, when assessing environmental impacts of steel products, it is a comprehensive approach that eliminates the distinction between products to be produced by melting iron ore (blast furnace products) and products to be produced primarily by melting scrap (electric arc furnace products), (refer Appendix C). Certain countries such as Switzerland do not follow this approach and quantify the environmental impacts of materials based on their actual share of recycled content.

5.6.2 New materials and systems

For building construction, new or emerging products can be applied. But many EEG studies assume common products and use generic EEG data. This is because their share and/or contribution is not relevant on the building level or because of a limitation of EEG data of new/emerging data.

In the survey of each country (see Appendix C), no respondents consider emerging products for their EEG quantification of buildings. One of the key reasons is data limitation (not available). Thus, most studies assume common data for emerging products unless EEG data is available.

5.6.3 Imported material

Imported material/products should require tracking upstream for the energy sources used in the country of production, transport distances etc. Different countries may have different energy carriers, level of emission control, use of various process gases (e.g., NF_3, SF_6 etc.) and energy efficiency of manufacturing processes. Also, each country has its particular electricity mix. Therefore, the same product may have different EEG depending on the where it is manufactured.

Figure 22 shows an example of EG of aluminum for different countries. To compare the EG of primary aluminium from different countries, various LCI data are used for quantification (Ecoinvent v3 for European, Australasian ver 2013 for Australian and US LCI (2013) for US). Using SimaPro software (ver 8.0) the EG emissions (greenhouse model as single point in kg of CO_{2eq} with 100 year timeframe and IPCC default) of aluminium are quantified for different countries. Also two other EG data from literature (primary aluminium from ICE database and Chinese primary aluminium from Gao et al., 2009) are taken into consideration for comparison.

As shown in Figure 27, 19 kg-CO_{2eq} are released in the manufacture of 1 kg of primary aluminum in Australia. While primary aluminium in US (US LCI ver 2013) releases 11.2-CO_{2eq} for the same amount of primary aluminium production, which is 41% less EG than the Australian product. European primary aluminium releases 70% less CO_{2eq} than the Australian product (13.3kg-CO_{2eq}). This is similar to the value in the literature (12.8 kg-CO_{2eq} per kg of primary aluminium, taken from ICE data). On the other hand, EG for primary aluminum in China is 21.5 kg-CO_{2eq}/kg of aluminum. Even though GHG intensity for Chinese power generation is similar to Australia (0.868 kg-CO_{2eq}/kWh, similar energy mix (83% for fossil fuel, 15% hydro and 2% for nuclear) the EG for Chinese aluminium are 13% more than Australian aluminum as shown in Figure 22.

Even for the same product, the EG can vary depending on the country of production. Thus, this should be considered for imported product.

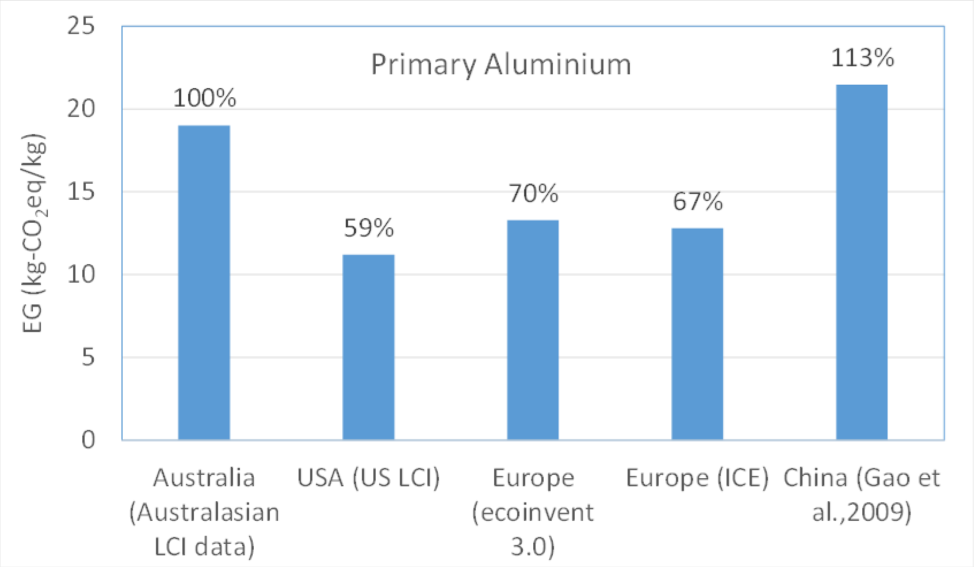


Figure 22 EG comparison for different countries

5.7 Transportation EEG

EEG from transportation includes energy and GHG emissions to deliver a product from the manufacturing plant to the construction site (A4 in Figure 5) and building site to waste processing site (C2 in Figure 5). The transportation distance of material/product from the manufacturing plant to the construction site or building deconstruction site waste processing site 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 compared to other life cycle stages, which consider embodied impacts (as shown in Figure 5).

Though transportation is not a major contributor to the total EEG emissions at the building level, it may not be small at the product level. Buchanan and Honey (1994) estimated transportation energy including construction energy accounts for 6.5% to 10% of the initial EE of building materials in a building. Cole and Rousseau (1992) also reported that transportation and construction energy consumption is up to 12% of the material EE (initial EE). Even some specific cases in Japan, Oka et al, (1993) report that energy consumption of transportation (manufacturing plant to construction site, A4 only in Figure 5) is responsible for 10% to 12% of the whole EE. Energy and GHG emissions from transportation should be taken into account in the embodied impacts.

The equations below give the energy and GHG emissions quantification from transportation of products or wastes. Energy or GHG emissions can be calculated by multiplying the transportation distance by the energy or GHG conversion factor, which can vary depending on the transportation modes.

$$Energy_{Trans} = \sum_{j,m} (T_j^t \times f_t^e)\ , \quad GHG_{Trans} = \sum_{j,m} (T_j^t \times f_t^c)$$

$Energy_{Trans}$ and GHG_{Trans} are the energy consumption and GHG emissions due to the transportation of products from the manufacturing plant to the construction site (or deconstruction site to waste processing site) (in MJ for energy and CO_{2eq} for GHG). T_j^m is the total transportation distance of the product from the manufacturing plant to the construction site (or deconstruction site to waste processing site) by transportation type (truck etc, in km). f_t^e and f_t^c are the energy and GHG emissions conversion factor for transportation by transportation type (in MJ/ton-km for energy or in kg-CO_{2eq}/ton-km for GHG).

Figure 23 presents relative carbon emissions for different transportation modes in Australia. For example, to transport 1 kg of product 1 km, 23.2 g-CO_{2eq} of carbon is released by shipping. For the same amount of product transported by truck, the carbon emissions can be increased by 4.5 or 16.7 times that of shipping in Australia (Figure 23). With the air freight, the carbon emissions are 73.7 times that of the shipping mode (Figure 23).

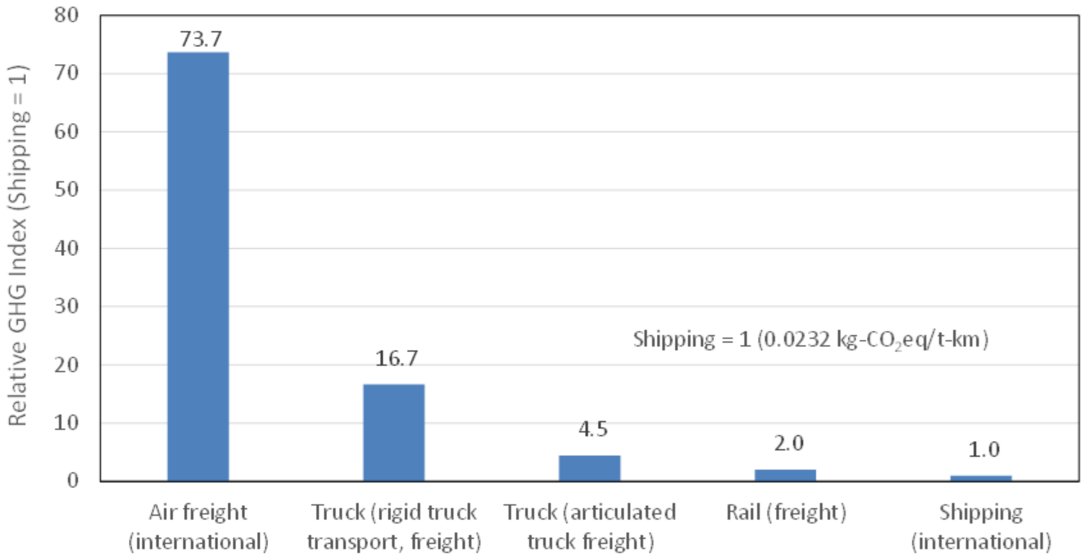


Figure 23 GHG emissions per ton-km for transport in Australia (SimaPro v8.0 with Australian unit process LCI ver 2013)

5.8 Site emissions

Energy consumption and GHG emissions from construction equipment comes from the fuel and electricity consumption of on-site equipment and/or heavy equipment to move, assemble or install building product/elements on site. Power tools (e.g., drills, welders, power cutters etc) consume electricity and fuels are consumed by heavy equipment such as cranes, loaders and forklifts. When looking at the whole life cycle of civil engineering work, material is responsible for 80% of total energy consumption and construction (particularly due to equipment usage) contributes 13% of total (van Gorkum, 2000).

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 of the interior.
During these activities, power (tools, lighting etc) and fuel (transport) are used on the construction site. Also, construction waste after installation of building products/elements/components, is transported into waste management systems (landfill, recycling centres etc).
Energy consumption (GHG emissions) of power tools or heavy equipment (e.g., cranes, generators, prestressing equipment, concrete pumps etc) can be quantified by converting the electricity to energy units for power tools or the fuel consumption data of heavy equipment. The energy consumption can be quantified using the following equation;

$$EG_{Equipment} = \sum_{i} (Running\ hours\ \times energy\ use_{Equip,i})$$

$EG_{Equipment}$ is energy consumption of equipment for building construction (MJ/m^2). Running hours are hours of operation of equipment (h). Energyuse$_{\text{Equip, i}}$ is energy demand per hour of equipment type i. (MJ/h) (i: crane, loader, backhoe, bulldozer, concrete cutter, pump car, etc). Energy consumption of equipment can be obtained by multiplying the running hours of equipment i by the standard energy demand of equipment type i. GHG emissions from equipment can be established by converting energy to GHG by multiplying the GHG intensity of the energy (fuel).

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 emissions from construction equipment are too small and thus negligible (Lemay, 2011; Seo and Hwang, 1998, 2001; Hacker et al., 2008; Junnila and Horvath, 2003) or underestimated its impacts (Hendrickson and Horvath, 2000). Some other studies assume that energy and GHG emissions are similar for building construction and thus use the results of other studies (e.g., Cole and Rousseau, 1992; Chen, S., 2011; Chen et al., 2012; Seo et al., 2014 etc), having 7% to 12% of the total EE (or EG) (Cole and Rousseau, 1992; Chen et al., 2012; Chen, 2011; Seo et al., 2014; Stein et al, 1976). In Switzerland the efforts for excavation and backfilling as well as deconstruction are taken into account whereas efforts required by further equipment such as (electric) cranes are negligible and thus excluded.

Net zero energy building or high energy efficient building is being common knowledge in building construction, the proportion of EE or EG against operational phase is being decreased. Correspondingly more material and products are required to get a net zero energy building or high energy efficient building, which may influence to increase on-site emissions to embodied impacts. Because of this, the proportion of on-site emissions to embodied impacts may be increased. Data which is relevant to on-site energy consumption or GHG emissions should be collected to take into account in the total EEG. Table 21 represents activities which consume energy and produce GHG emissions at the construction site.

Table 21 Energy/GHG emissions of activities at the construction site

Activities	Energy/GHG from	Data collection
Site preparation	Machinery, lighting	Machinery use time, machinery energy consumption, lighting energy consumption
Installation component/assembly	Machinery, lighting	
Transportation from factory gate to the site	Fuel	Material/product weight, distance from factory gate to construction site, transportation mode
Transportation from site to waste management system	Fuel	Waste amount, distance from site to waste management facility, transportation mode.

Once all the data (machinery and tool usage on site, material amount and distance to the site etc) are obtained from the contractors and/or suppliers, energy and GHG emissions for construction site can be obtained multiplying these data by energy/GHG intensity for each of the data. However, it is not easy and requires lot of efforts. Thus, alternatively, quantify the amount of soil to be excavated (and partly backfilled) and link it to a diesel consumption of heavy equipment per m3 excavated. With this the main share of on-site energy consumption and GHG emissions is captured.

5.9 Waste management

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

According to BAM (2014) which is one of the biggest construction companies in the UK, GHG emissions from construction, demolition (or dismantle of material/equipment for temporary work) and excavation waste was reported as 35,000 t-CO_{2eq} from all their construction sites. Of these emissions, almost 86% (30,000 t-CO_{2eq}) is due to the EG in materials, which include transportation and treatment of wastes. Of these wastes stream, the key wastes which influenced the GHG emissions was mixed packaging and plastics having 10% of total waste and mixed construction waste (63%).

WRAP (2014) estimates about 4% of in-situ concrete goes to waste from the construction site. Due to over-ordering and mishandling of products at the site, up to 20% of bricks are wasted on site. Metals and timber, which are key building materials, have a waste component of 10% (Table 22).

Table 22 Construction waste amount

	Concrete	Brick	Metal	Timber	Finish		
					Plasterboard	Plaster	Carpet
Waste(%)	4%	20%	10%	10%	23%	5%	20%

Source: WRAP (2014)

Wastes are generated when a building is constructed or demolished. Wastes also come from retrofitting of buildings. Each phases consumes energy and releases GHG due to waste collection, transportation of waste from the site to the waste station/material recovery facility/landfill site. Also, energy can be consumed during each phase due to the running of equipment to process or deconstruct the building. This energy consumption boundary due to waste treatment is shown in Figure 24.

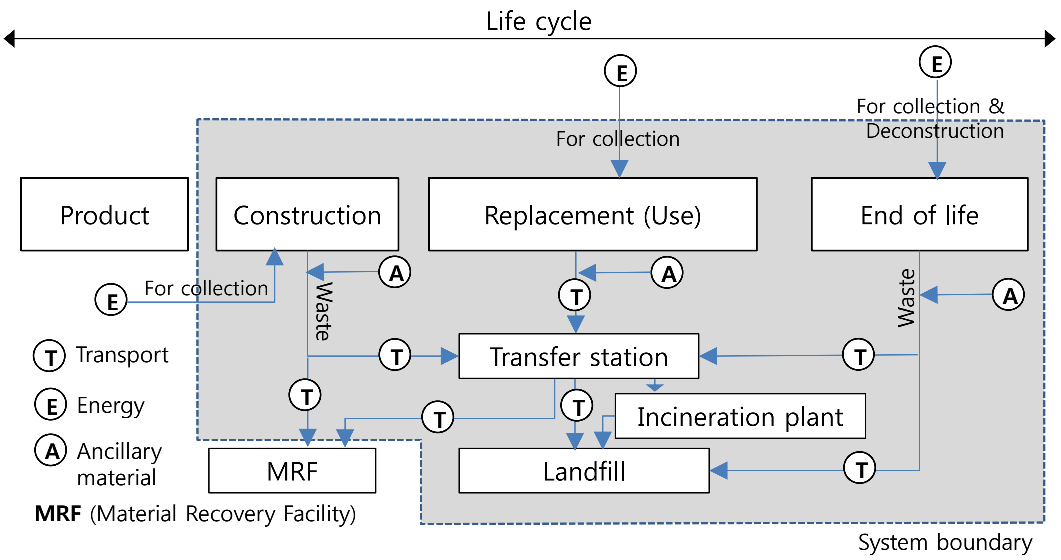


Figure 24 System boundary of EEG from waste treatment

Energy and GHG emissions of waste treatment are mainly due to the energy consumption for transportation of waste to the treatment plant, and energy consumption of equipment used for waste processing and final disposal. Thus, the EEG of waste treatment can be represented as follows;

$$EE_{Waste} = \sum_{i,k} \{E_i + (C_k \cdot f_{ke})\} + E_T \quad \text{or} \quad EG_{Waste} = \sum_{i,k} \{(E_i \cdot f_{ic}) + (C_k \cdot f_{kc})\} + G_T + G_{Inc}$$

where,
EE_{Waste}: EE from waste treatment (*MJ*)
E_i: Direct energy consumption of type *i* which is consumed in the waste treatment *(MJ/ton of waste, i* = energy type such as electricity, diesel, LNG etc.),
C_k: resource consumption of type k which is consumed in the waste treatment (*kg/ton of waste, k* = resource type such as ancillary material used in the waste treatment),
f_{ke}: EE coefficient of resource k (*MJ/kg of resource k*),
E_T: Energy consumption due to transport of waste (*MJ/ton of waste*)
EG_{Waste}: EG from waste treatment (*kg-CO*$_{2eq}$)
f_{ic}: GHG emission factor of energy type *i (kg-CO*$_{2eq}$ */MJ of energy type i*),
f_{kc}: GHG coefficient of resource type *k (kg-CO*$_{2eq}$ */kg of resource type k*),
G_T: GHG emissions due to transport of waste (*kg-CO*$_{2eq}$ */ton of waste*)
G_{Inc}: GHG emissions due to incineration of wastes (*kg-CO*$_{2eq}$ */ton of incinerated waste*)

The GHG emission factor for energy consumption (f_{ie}) are given by the emission factor recommended by IPCC (2006a) or by national databases supporting the assessments of EEG of buildings except for electricity. In the case of electricity, each country has different GHG emissions factors due to different energy mixes for electricity generation. The GHG emissions data due to resource consumption (f_{kc}) can be taken from the commercial LCI or EEG database.
EEG of waste transportation is influenced by transportation mode, distance and waste amount generated on site.

5.10 Input Output Analysis

5.10.1 Introduction

This section aims to understand the values of EEG for building construction and civil engineering in individual countries and to identify the research objective of Annex 57 in a quantitative manner. Generally, the calculation of EEG for buildings involves the multiplication of the EEG in a database for a given unit of individual materials (e.g. MJ/t, kg-CO$_{2eq}$/t) and their quantities used (e.g., ton, m^3, etc.). The last section provides a method for calculating EG for construction in individual countries according to the IO analysis approach.

5.10.2 Worldwide Input Output Analysis

5.10.2.1 Data source

The Symmetry IO table and the System of National Accounts (SNA) table for 40 major countries around the world from 1995 to 2009 are made available to the public (Table 23, WIOD, 2015). The number of industrial sectors in the Symmetry IO table is 35. The SNA-use matrix is a table listing the amounts of input in terms of 59 commodities corresponding to 35 sectors. The units used in the table are currencies in individual countries and the United States dollar. A database that shows changes in CO$_2$ emissions across the ages in each country due to gas fuels, liquid fuels, solid fuels and cement production is also publicly available (Boden et al., 2013).

Table 23 Country names of World IO

No.	Country	No.	Country	No.	Country	No.	Country
1	Australia	11	Denmark	21	Ireland	31	Poland
2	Austria	12	Spain	22	Italy	32	Portugal
3	Belgium	13	Estonia	23	Japan	33	Romania
4	Bulgaria	14	Finland	24	Korea	34	Russia
5	Brazil	15	France	25	Lithuania	35	Slovak Republic
6	Canada	16	UK	26	Luxembourg	36	Slovenia
7	China	17	Greece	27	Latvia	37	Sweden
8	Cyprus	18	Hungary	28	Mexico	38	Turkey
9	Czech Republic	19	Indonesia	29	Malta	39	Taiwan
10	Germany	20	India	30	Netherlands	40	USA

5.10.2.2 Calculation method and the result

Using WIOD, the EEG can be obtained with following procedure.

(1) Create Leontief inversion of the Symmetry matrix

(2) Calculate X_{ti} and X_{ci}, the domestic total output (X_{ti}) of 35 sectors by entering the total domestic consumption expenditure, and the domestic output (X_{ci}) by entering the domestic consumption expenditure for construction industry in the inversion

(3) According to the SNA-use matrix, calculate the amount of input in Japanese yen from the coal and lignite sector and the crude petroleum and natural gas sector for 35 sectors, from which

we will obtain UC_{ti} and UP_{ti} corresponding to X_{ti}, as well as UC_{ti} and UP_{ci} corresponding to X_{ci}.

- UC_{ti}, UP_{ti}: Input from coal/lignite sector and crude petroleum/natural gas sector for X_{ti}
- UC_{ci} and UP_{ci}: Input from coal/lignite sector and crude petroleum/natural gas sector for X_{ci}

(4) CF obtained in the following formula serves as EG originating from fossil fuels consumed due to construction demand, assuming that CO_2 emissions are proportional to the amount of input.

$$CF = \left\{ \left(\frac{\sum UC_{ci}}{\sum UC_{ti}} \right) \times CCE \right\} + \left\{ \left(\frac{\sum UP_{ci}}{\sum UP_{ti}} \right) \times CPE \right\}$$

where,
CF: EG (t-CO_2) originating from fossil fuels required due to construction demand
CCE: GHG emissions (t-CO_2) originating from coal and lignite
CPE: GHG emissions (t-CO_2) originating from crude petroleum and natural gas

In the Symmetry matrix in most countries, figures of import/domestic demand in terms of coke, refined petroleum and nuclear fuel input for 35 sectors are fixed at a certain value in all types of industry.

(5) The GHG emissions from cement are calculated in the same manner as that of fossil fuels, assuming that it will be proportional to other non-metallic mineral products, the value of which is used as CC originating from cement production. EG due to construction is expressed as CF+CC (t-CO_2).

The comparison of calculation results based on the 401 industrial sector IO table and 35 industrial IO table of Japan, 2005 is shown in Table 24. Table 25 shows a comparison/contrast of CO_2 intensities between industrial sectors in the 401 industrial sector IO table and those in the 35 industrial IO table. In terms of iron/steel and non-ferrous metals having a wide range of items, hot rolled steel in the 401 sector table does not correspond to basic metals and fabricated metal. However, EG per ton of iron/steel is approximately the same value in the two tables.

Table 24 Comparison of IO analysis between 401 and 35 industrial sector IO tables of Japan

	IO of Japan (401 sectors)	**IO (35 sectors) + Use matrix (59 sectors)**
GDP (million Yen)	972,014,632	953,828,818
Construction – Final demand (Million Yen)	53,540,506	59,696,410
Total CO_2 emissions in Japan (1000 t-CO_2)	1,291,444	1,203,454
Fraction of CO_2 emissions due to construction	13.5%	14.6%

Table 25 Comparison of CO_2 intensities between 401 and 35 industrial sector IO tables of Japan

IO in Japan (401 sector)		**World IO (35 sectors)**	
Industrial sector	**CO_2 intensity (kg-CO_2/million yen)**		**Industrial sector**
Timber	769	1788	Wood and products of wood and cork
Plywood	1594		
Wooden furniture and fixtures	1402		
High functionality resins	5975	6242	Chemicals and chemical products
Plastic products	4763		
Sheet glass and safety glass	2999	7279	Other non-metallic minerals
Glass fibre and glass fibre products	5732		
Cement products	7985		

Hot rolled steel	22135	6757	Basic metals and fabricated metal
Steel pipes and tubes	13374		
Other iron or steel products	5329		
Copper	1756		
Aluminium (inc. regenerated aluminium)	1308		
Boilers	2057	1814	Machinery
Refrigerators and air conditioning apparatus	1970		
Residential construction (wooden)	1707	3395	Construction
Non residential construction (non-wooden)	2704		
Public construction for roads	3451		
Road freight transport service	3132	2700	Inland transport

5.10.3 EG emissions

5.10.3.1 Worldwide EG

EEG in Japan

The EEG are obtained from the analysis of IO (input/output) tables. The IO tables of Japan consist of 401 industrial sectors. The domestic output of each industrial sector can be calculated by Leontief inversion with domestic consumption expenditure as explained in 3.2.2 Input-Output analysis.

The total annual GHG emissions in Japan, where the corresponding fractions of EG due to building construction and civil engineering, and the GHG emissions due to building operation that are estimated by the Input-Output analysis are shown in Figure 21. EG is 19.2% and the operation of buildings is 23.2% of the total GHG emissions in Japan.

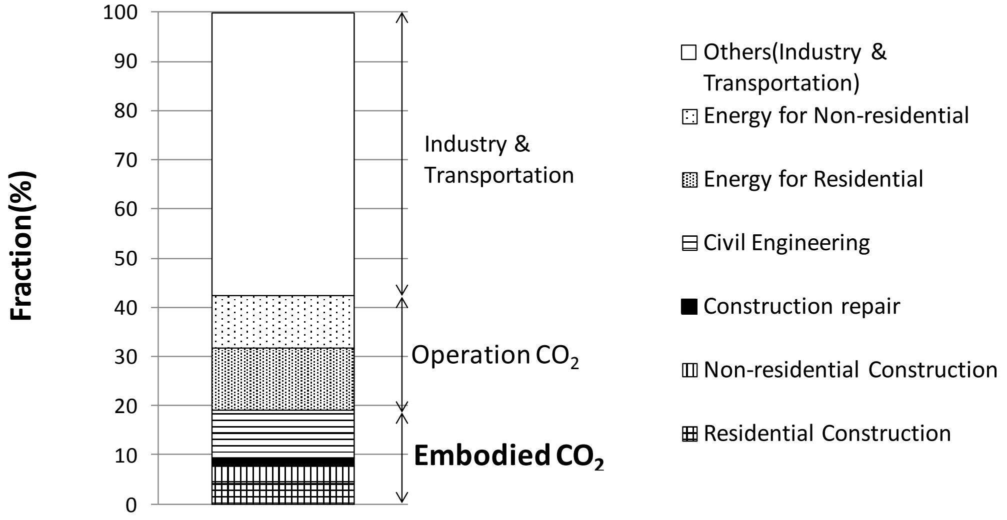


Figure 25 Fraction of EG due to building construction and operation in Japan, 2005 (total GHG emissions in Japan in 2005 is 1.29 billion t-CO$_{2eq}$)

Fraction of worldwide EG

An estimation of the total CO_2 emissions in various countries and the corresponding fractions of EG due to building construction and public works are shown as a result of analysis of world IO tables in Figure 26. In particular, fractions of EE are higher in developing countries and often exceed the building operation energy. The EE differs among countries depending on 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 CO_2 emissions. Regarding EG, though it is certainly important to reduce the current EG, we could also consider means of greatly reducing the future EG by slightly increasing life span of buildings. 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.

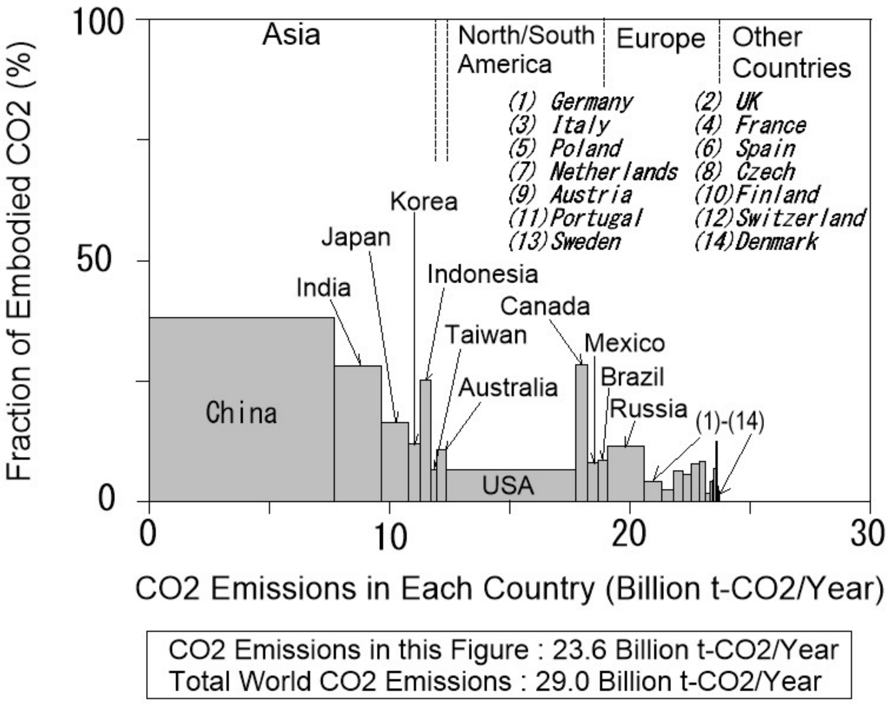


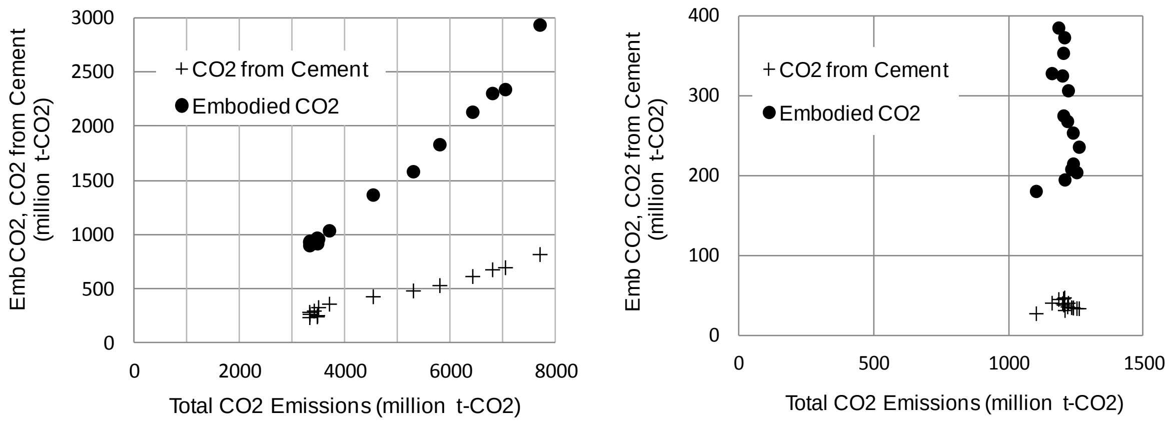
Figure 26 Total CO_2 emissions in each country and the fraction of Embodied CO_2

Annual change of EG from cement production

Cement and iron/steel used as structural materials in building construction and civil engineering account for a large fraction of EG. Figure 27 shows the annual EG due to construction and GHG emissions from cement production (Boden et al., 2013).

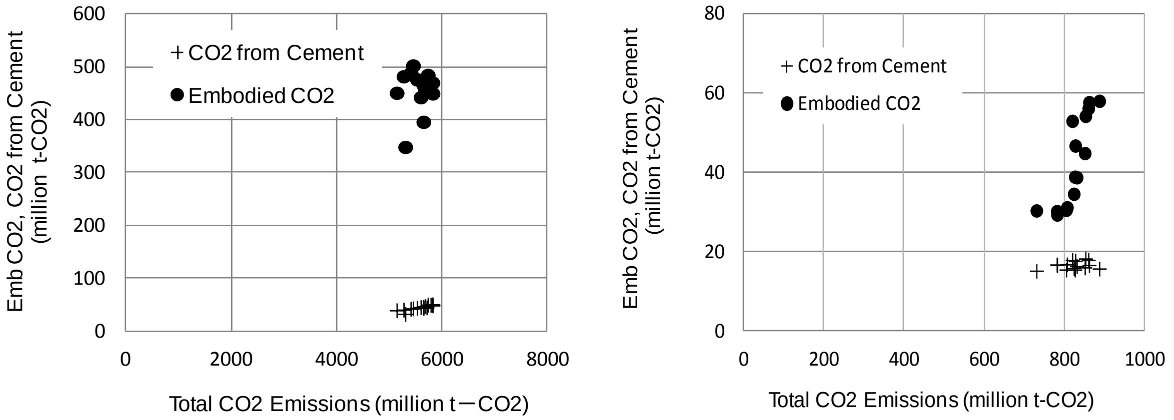
In China, EG due to construction and GHG emissions from cement production have been increasing every year at a constant rate. The GHG emissions from cement production in Japan are generally fixed, whereas EG has been on the decrease year by year.

In the USA, the GHG emissions from cement production are low compared to EG, whereas this ratio is relatively high in Germany. We can assume that this is due to the difference between building structures and the amount of cement consumed per area of floor space. Further, by the nature of the IO calculation, as cement products are allotted in proportion to other non-metallic mineral products, in some cases, it may be allotted more to other industrial sectors in the calculation.



(1) China: 1995~2005

(2) Japan: 1995~2005



(3) USA: 1995~2009

(4) Germany: 1995~2009

Figure 27 Relationship between EG for construction and GHG emissions from cement production

EG per capita

Figure 28 shows the comparison of EG from construction per capita and year? among individual countries. EG values are high in Asia (0.5-2 t-CO_2/person), the USA (1.1 t-CO_2/person) and Australia (1.9 t-CO_2/person), whereas EG from construction per capita in Europe is low (0.2-0.7 t-CO_2/person). The large value in Canada (4.4 t-CO_2/person) is due to the fact that the fraction of EG to the entire CO_2 emissions is as high as 28.4%, as well as a large amount of energy is consumed directly by the construction sector.

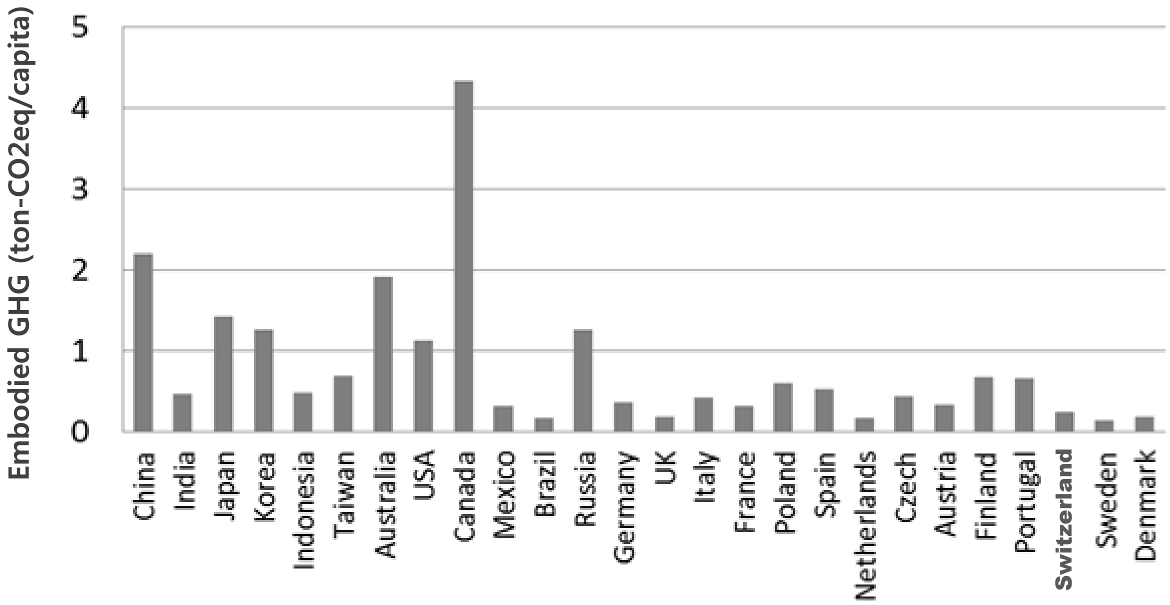


Figure 28 EG due to construction per capita/year, 2009

5.10.4 Summary

This section showed EG in Japan and other countries throughout the world according to the IO analysis, in order to quantify the fraction of EG that accounts for the entire CO_2 emissions. Throughout this example, the following observations are made:

- Results of EG from construction in individual countries based on the World IO table, EG(CO_2) accounts for 20.3% of the entire CO_2 emissions on average worldwide. EG is high in Asian countries ranging from 10% to 38% (19.2% for Japan). EG in the USA and European counties is lower, accounting for 6.6% and around 5% to 10%, respectively.
- Calculation results of EG per capita in individual countries indicate that it is 0.5-2 t-CO_2/person in Asia and the USA, and 0.2-0.7 t-CO_2/person in Europe.

6. Summary and recommendations

EEG have been attracting great attention due to their growing impact in the life cycle of buildings. There are a number of tools and models available to assist in achieving the goal of reducing EEG of buildings. However, there is a lack of practical technical information about the currently available methodologies on how to quantify EEG, and their relative comparisons and differences.

This report, as one of the subtasks of Annex 57 (Subtask 3: Evaluation methods for EEG), presents the different types of data sources and calculation methodologies to evaluate EE and GHG emissions, based on a common framework and transparent reporting format. Also this report discusses the specific issues which need to be considered in quantification of EEG which may lead, if ignored, to inappropriate decision making for reduction of EEG.

The important technical features of each methodology have been presented to inform appropriate interpretation and application of results. The critical factors and considerations that influence computed or provided EEG values were discussed. Particularly, this report reiterated the definition and boundary of EEG of buildings and building products which is important to interprete the final results. Based on the definition and boundaries, calculation methods, which are currently used throughout the world, were discussed to help the decision makers enhance their understanding of the difference between methods, requirements and procedures including technical features of each of the approaches.

To help understand the existing database, this report presented how to create the EEG data. This helps decision makers to create the fundamental data for EEG. The following six minimum requirements increase the credibility of embodied data: materiality, consistency, transparency, timeliness, reliability and quality control. Even though these are not required for general quantification of embodied impacts, they are required for the professional work to develop the fundamental database for EEG for building materials.

It is important to understand not only the initial embodied impacts but also the recurring embodied impacts, which may significantly affect total embodied impacts. An illustrative example of streamlined quantification for commercial building shows that total EE or EG is 2.5 times the initial embodied impacts. This example shows how efficient selection of building materials can reduce the total embodied impacts in the building design stage and the recurring embodied impacts are highly affected by the building service life.

There is still debate as to whether fluorinated gas emissions (coolant leakage etc.) from buildings should be included in the EG. This report shows the significant contribution of these emissions to total GHG emissions of buildings. If used in significant amounts, not only fossil fuel consumption should be considered as contributing to GHG emissions in the operational stage but also coolant leakages. If these emissions are significant but not included in the operational emissions, it is important to consider them as EG emissions of building.

This report also discussed a number of key considerations including recycled/reused material, imported material, waste management, transportation and on-site emissions.

A macro (country-level) approach to quantify the EEG for the building construction industry is demonstrated using the world IO table. This could help policy makers to identify the key industries affecting building construction in their country and also provide useful information to understand and compare embodied indicators for building construction between different countries.

The following recommendations are made:

- All stakeholders need a clear understanding of definitions and use of terminologies such as EEG, life cycle stages, etc. (see Chapter 2).
- Both data suppliers and particularly data users need to provide and understand, respectively, the minimum information requirements about the bases of any EEG values, i.e. based on the reporting framework and format in Chapter 2 and Chapter 4.
- The stakeholder's purpose of evaluation should be clearly stated and understood to guide the selection of appropriate datasets (if there are options or choices) that will best support the decision making process.
- Data users and decision makers should avoid comparing EEG values that have clear incompatibilities of methodology, system boundary and included emissions, unless these differences and their potential impacts on these values are understood.
- All involved should keep abreast of continued developments in research and practice, guidelines and standards, esp. in sources and types of new or updated data or databases, evaluation methods, application examples, etc. They should also continue to learn lessons from their own practice or experience and share them in their communities of practice.
- Specific considerations should be made when quantifying EEG as described in Chapter 5.4-5.6. These include;
    - Service life of products
    - Influence of GHG emissions beyond the fossil fuel based sources (fluorocarbon)
    - Clarification of other impacts (recycled/reused, imported, waste, transportation, on-site emission, and waste management).

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Appendices

Appendix A GHGs included in IPCC

The below lists the 100 year time horizon global warming potentials (GWP) based on IPCC firth assessment report (IPCC 2013). Please see the IPCC website (www.ipcc.ch) for the further details.

Table A1 Global warming potential (GWP) relative to CO2

Industrial designation or common name	Chemical formula	GWP for 100 year time frame
Carbon dioxide	CO2	1
Methane	CH4	28
Nitrous oxide	N2O	265
Substances controlled by the Montreal Protocol		
CFC-11	CCl3F	4,660
CFC-12	CCl2F2	10,200
CFC-13	CClF3	13,900
CFC-113	CCl2FCClF2	5,820
CFC-114	CClF2CClF2	8,590
CFC-115	CClF2CF3	7,670
Halon-1301	CBrF3	6,290
Halon-1211	CBrClF2	1,750
Halon-2402	CBrF2CBrF2	1,470
Carbon tetrachloride	CCl4	1,730
Methyl bromide	CH3Br	2
Methyl chloroform	CH3CCl3	160
HCFC-21	CHCl2F	148
HCFC-22	CHCLF2	1,760
HCFC-123	CHCl2CF3	79
HCFC-124	CHClFCF3	527
HCFC-141b	CH3CCl2F	782
HCFC-142b	CH3CClF2	1,980
HCFC-225ca	CHCl2CF2CF3	127
HCFC-225cb	CHClFCF2CClF2	525

IPCC, 2013 Fifth report.

Table A1 (Continued)

Industrial designation or common name	Chemical formula	GWP for 100 year time frame
Hydrofluorocarbons (HFCs)		
HFC-23	CHF3	12,400
HFC-32	CH2F2	677
HFC-41	CH3F2	116
HFC-125	CHF2CF3	3,170
HFC-134	CHF2CHF2	1,120
HFC-134a	CH2FCF3	1,300
HFC-143	CH2FCHF2	328
HFC-143a	CH3CF3	4,800
HFC-152	CH2FCH2F	16
HFC-152a	CH3CHF2	138
HFC-161	CH3CH2F	4
HFC-227ea	CF3CHFCF3	3,350
HFC-236cb	CH2FCF2CF3	1,210
HFC-236ea	CHF2CHFCF3	1,330
HFC-236fa	CF3CH2CF3	8,060
HFC-245ca	CH2FCF2CHF2	716
HFC-245fa	CHF2CH2CF3	858
HFC-365mfc	CH3CF2CH2CF3	804
HFC-43-10mee	CF3CHFCHFCF2CF3	1,650
Perfluorinated compounds		
Sulfur hexafluoride	SF6	23,500
Nitrogen trifluoride	NF3	16,100
PFC-14	CF4	6,630
PFC-116	C2F6	11,100
PFC-218	C3F8	8,900
PFC-318	c-C4F8	9,540
PFC-31-10	C4F10	9,200
PFC-41-12	C5F12	8,550
PFC-51-14	C6F14	7,910
PCF-91-18	C10F18	7,190
Trifluoromethyl sulfur pentafluoride	SF5CF3	17,400
Perfluorocyclopropane	c-C3F6	9,200

IPCC, 2013 Fifth report.

Table A1 (Continued)

Industrial designation or common name	Chemical formula	GWP for 100 year time frame
Fluorinated ethers		
HFE-125	CHF2OCF3	12,400
HFE-134	CHF2OCHF2	5,560
HFE-143a	CH3OCF3	523
HCFE-235da2	CHF2OCHClCF3	491
HFE-245cb2	CH3OCF2CF3	654
HFE-245fa2	CHF2OCH2CF3	812
HFE-347mcc3	CH3OCF2CF2CF3	530
HFE-347pcf2	CHF2CF2OCH2CF3	889
HFE-356pcc3	CH3OCF2CF2CHF2	413
HFE-449sl (HFE-7100)	C4F9OCH3	421
HFE-569sf2 (HFE-7200)	C4F9OC2H5	57
HFE-43-10pccc124 (H-Galden 1040x)	CHF2OCF2OC2F4OCHF2	2,820
HFE-236ca12 (HG-10)	CHF2OCF2OCHF2	5,350
HFE-338pcc13 (HG-01)	CHF2OCF2CF2OCHF2	2,910
HFE-227ea	CF3CHFOCF3	6,450
HFE-236ea2	CHF2OCHFCF3	1,790
HFE-236fa	CF3CH2OCF3	979
HFE-245fa1	CHF2CH2OCF3	828
HFE 263fb2	CF3CH2OCH3	1
HFE-329mcc2	CHF2CF2OCF2CF3	3,070
HFE-338mcf2	CF3CH2OCF2CF3	929
HFE-347mcf2	CHF2CH2OCF2CF3	854
HFE-356mec3	CH3OCF2CHFCF3	387
HFE-356pcf2	CHF2CH2OCF2CHF2	719
HFE-356pcf3	CHF2OCH2CF2CHF2	446
HFE 365mcf3	CF3CF2CH2OCH3	<1
HFE-374pc2	CHF2CF2OCH2CH3	627
Perfluoropolyethers		
PFPMIE	CF3OCF(CF3)CF2OCF2OCF3	9,710
Hydrocarbons and other compounds - direct effects		
Chloroform	CHCl3	16
Methylene chloride	CH2Cl2	9
Methyl chloride	CH3Cl	12
Halon-1201	CHBrF2	376

IPCC, 2013 Fifth report.

Appendix B Calorific values (HHV) and CO_2 intensity

Table B1. Calorific values (HHV) and CO_2 emission factors by fuels

Fuel	Unit	Calorific Value	GHG emission factor	
		MJ/unit	kg-CO_2eq/unit	kg-CO_2eq/MJ
Lignite	kg	28.9	2.506	0.0867
Crude oil	L	38.2	2.613	0.0684
Natural gas	m3	40.9	2.020	0.0494
Gasoline	L	34.6	2.322	0.0671
Jet Fuel	L	36.7	2.463	0.0671
Kerosene	L	36.7	2.492	0.0679
Light oil	L	38.2	2.624	0.0687
A heavy oil	L	39.1	2.710	0.0693
B/C heavy oil	L	41.1	2.922	0.0711
Naphtha	L	34.1	2.271	0.0666
LPG	kg	50.2	3.002	0.0598
Coke	kg	30.1	3.251	0.1080
Limestone	kg	-	0.440	-

Yokoo et al. (2015)

Table B2. Energy consumption/CO_2 emission intensity

Part	Industrial sector*	Energy (MJ)	CO_2eq(kg-CO_2)	Unit (Mil. JPY+)
		Per consumer price of Mil. JPY	Per consumer price of Mil. JPY	Quantity of material for consumer price of Mil. JPY**
1	Gravel and quarrying	52,153	3,626	287.5 t
2	Timber	13,621	952	22.68 m^3
3	Plywood	22,697	1,599	7.0 m^3
4	Paints and varnishes	71,604	4,937	-
5	Plastic products	56,893	3,971	-
6	Sheet glass and safety glass	36,902	2,636	1,413 m^2
7	Glass fiber and glass fiber products, n. e. c.	71,691	4,842	
8	Cement	315,036	80,992	124.4 t
9	Ready mixed concrete	81,093	16,745	62.6 m^3
10	Cement products	43,193	5,994	-
11	Ceramics	54,376	3,500	-
12	Hot rolled steel	189,779	18,271	13.47 t
13	Steel pipes and tubes	119,963	11,182	6.158 t
14	Coated steel	90,489	7,958	9.002 t
15	Cast iron pipes and tubes	102,598	8,701	8.061 t
16	Electric wires and cables	22,562	1,611	0.645 conductor-t
17	Rolled and drawn copper and copper alloys	25,609	1,803	1.255 t
18	Metal products for construction	63,388	5,577	-
19	Metal products for architecture	35,353	2,878	-
20	Bolts, nuts, rivets and springs	45,000	3,859	-
21	Metal containers, fabricated plate and sheet metal	45,951	3,798	-
22	Boilers	22,980	1,832	-
23	Refrigerators and air conditioning apparatus	23,502	1,808	-
24	Pumps and compressors	27,127	2,238	-
25	Electric transformer	21,509	1,727	-
26	Relay switches and switch boards	22,878	1,780	-
27	Electric lighting fixtures and apparatus	24,345	1,770	284 p
28	Batteries	28,099	2,026	5091 p
29	Air conditioning equipment for consumer use	21,210	1,577	11.13 p
30	Residential construction (wooden)	19,921	1,707	6.318 m^2
31	Residential construction (non-wooden)	29,055	2,704	5.527 m^2
32	Non-residential construction (wooden)	21,103	1,835	7.749 m^2
33	Non-residential construction (non-wooden)	29,644	2,704	6.844 m^2
34	Repair of construction	27,466	2,436	-
35	Waste disposal services (public)	44,332	3,155	-
36	Waste disposal services (industrial)	26,296	1,880	-
37	Building maintenance services	7,753	548	-
38	Civil engineering and construction services	11,234	801	-

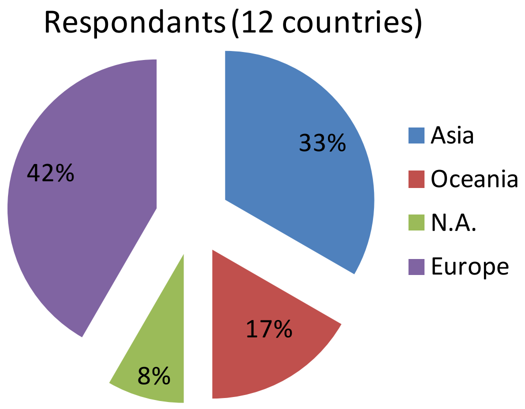
*Listing only major industrial sectors engaged in construction businesses from all the 401 types of industry: 1 Mil. JPY = 9,091US$, year 2005

**Leaved blank for some industrial sectors which produced multiple products (since no single product from these industrial sectors)

+ Million of Japanese yen (Mil. JPY).

Appendix C Preliminary survey of EEG data

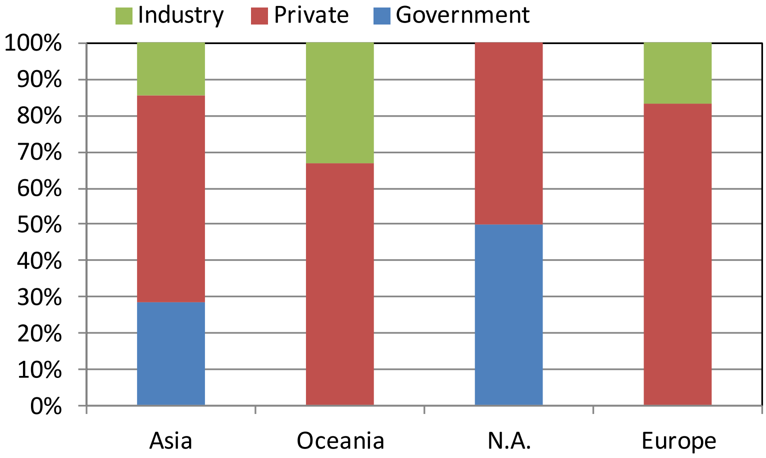
Preliminary survey for Embodied energy (EE) and Embodied GHG (EG).



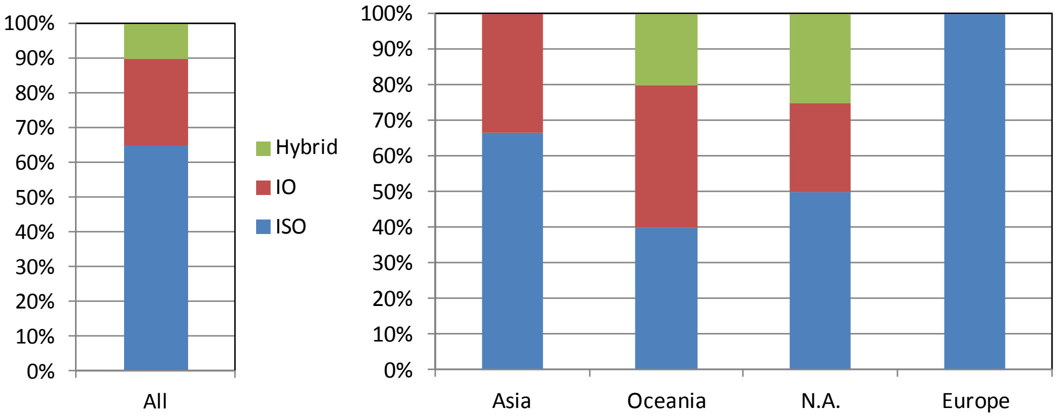
Preliminary questions

1. Do you have embodied GHG database for building/building materials in your country?
    A. If you have, which organization manages the database?
2. Which methodology used (or dominant) for the database development?
3. When evaluate EEG, how to consider 'Emerging' building products?
4. When evaluate EEG, do you, in general, consider 'capital'?
5. How to consider 'imported product' for your EEG?
6. How to consider 'recycled/reused material' in EEG in your study?
7. Do you consider energy consumption/GHG emission from 'on-site'?

1. EEG databases appeared to be mainly maintained by private (university etc) particularly in Europe Oceania and Asia. However, in USA and Asia, governments also involve maintaining the database.



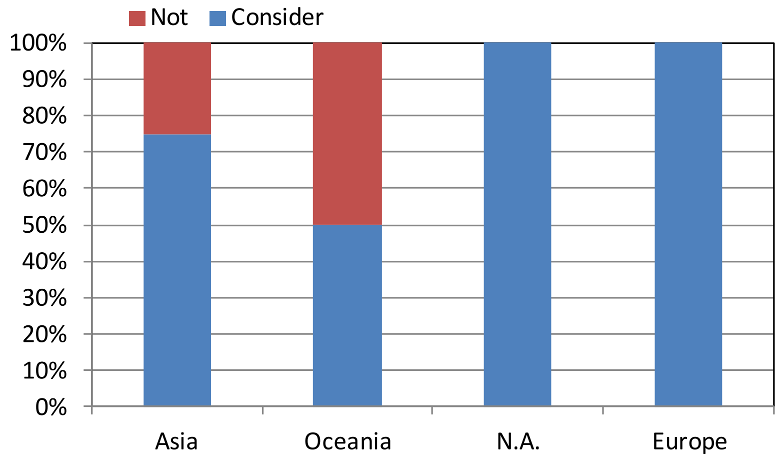
2. In the preliminary survey, quantification method is shown ISO process approach dominant having 65% of respondents. But also, economic Input/output method showed to be used in other countries. But in Europe, it appeared to be used only ISO process method for EEG quantification.



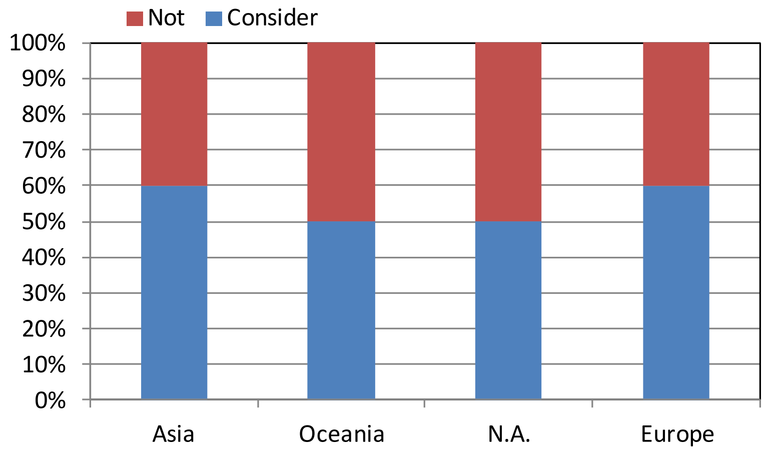
3. When quantified EEG, most of respondents answered not to consider ‘emerging building product’ except for EPD data or manufacturing data available.

4. For energy and GHG emission from ‘Capital’, only Japan and New Zealand responded to consider for energy and GHG emission from the ‘Capital’ in the preliminary survey.

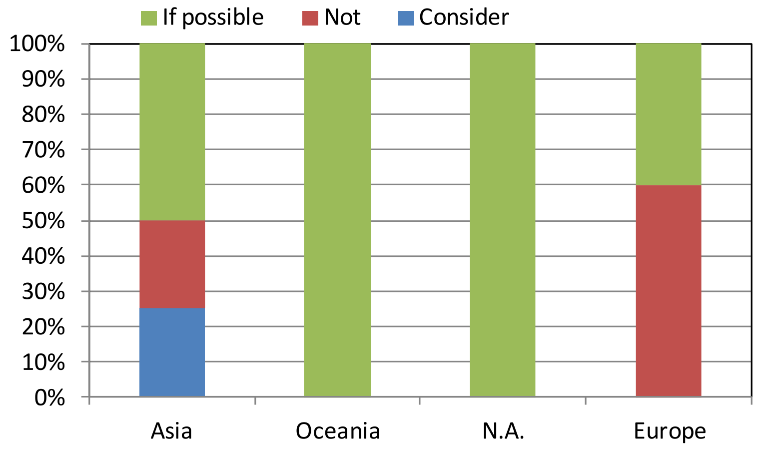
5. In the preliminary survey, most countries (83%) considered imported products for their EEG quantification, but some countries responded to be assumed as domestic product due to the limitation of data availability.



6. For ‘Recycled/reused product’ in EEG quantification, some countries do not consider recycled/reused product’ due to the limitation of data. Instead they assumed to be produced with primary material. However, most of respondents answered if enough data available for recycled/reused information, then they can consider otherwise, they assumed to be produced with primary material.



7. Only few respondents answered to consider ‘on-site energy consumption and GHG emissions’ for their EEG of building. The key reason is limitation of data available for ‘On-site’ energy/GHG emission. Many of respondents (58%) answered use the data if data is available.



Appendix D EEG data for each country

D. 1 Asia

Depending on the increase of awareness and concerns of LCA, many Asian countries have been developing their own national LCI database (eg., China, Japan, Korea, Malaysia, Thailand etc). But the data for building products are a little early stage except for Japan and Korea and recently China.

- Japan

Japan has developed broad LCI data for various products including building products. Variety methods (economic Input/Output, process model, statistics etc) are used to develop LCI and/or EEG data in Japan. Particularly Japanese government agency (NIES, National Institute of Environmental Studies) periodically release EEG data using economic Input-Output tables since 2002. The database is called 3EID (EE and Emission Intensity Data). Recent data is based on 2005 Input-Output table, which covers more than 400 commodity sectors including building industry. The database can be freely downloaded from the website
(http://www.cger.nies.go.jp/publications/report/d031/eng/page/what_is_3eid.htm).
3EID example data are shown in Table D1.

Table D1. Embodied environmental intensities on the producer's price basis

	Detailed sector	Small sector	Middle sector	Large sector
Intensity	Energy & CO_2			
Unit	TOE/Million yen for energy & Ton-C/million yen for CO_2			
Sector	401*	188*	104*	32*
Example	0.586 ton-C/million yen of residential building (wooden) construction	0.711 ton-C/million yen of residential building construction	0.777 ton-C/million yen for Construction	0.759 ton-C/million yen for Construction

*including building industry sector (the larger the sector, more accurate of data)
Source: NIES 3EID database in 2000

- Korea

Korea has been developed EEG data for building materials using energy Input-Output model (Seo, 1998; Seo et al., 1999) and life cycle GHG data for building materials using economic input-output table (Shin et al (2008)) But these are mostly private and academic purposes based on input-output approach. Recently Korean government (MOCT, Ministry of Construction and Transportation) initiated to develop LCI database for building materials and processes in 2004 based on process approach. Currently more than 87 modules for building industry has been developed (556 modules for whole industries) using process method. Currently KICT (Korean Institute of Civil Engineering and Building Technology) has been updating EG database for building materials (CTN, 2012).

- China

China does not have any separate embodied data for building materials. IKE (IT & Knowledge for Environment, www.itke.com.cn) leads to development of Chinese core LCI database (CLCD) including building materials. Currently IKE has been developing more than 140 unit processes for key building materials (concrete, metal, steel, aluminium, aggregates etc) using process method (Table D2).

Table D2 Chinese Life Cycle Database (CLCD) for building products

Building product	Modules
Concrete	25
Metal	43
Steel	40
Aluminium	10
Aggregates	8
Glass product	1
Other	13
Total	140

Source: Email communication (2013)

- Oceania

Over the past 15 years or so, several organizations in Australia have embarked on developing LCI data for a selected range of building products. Particularly BP (Building Product) LCI, FWPA EG data, RAIA and other academic databases are more focused on building material/product (Table D3). RAIA data is frequently used by Australian industry for their EE quantification, but its age represents a weakness for many products. On the other hand, BP LCI data, with recently updated FWPA timber LCI data, has increased its breadth of data for building/construction industry application.

Table D3 General overview of LCI/embodied data which are available in Australia

DB	Purpose	Provider	Unit	Data #	Cover-age	Data source	Usability
BP LCI	LCI for building products	BPIC*	Emission/SI unit kg, m^2 etc.)	<50	LCI (gate-to gate)	Industry	Open
FWPA embodied carbon	Emb. C for AccuRate	FWPA via Hearne Scientific	kg-CO_{2eq}/SI unit (kg, m^2 etc.)	<70	Emb. C (cradle-to gate)	Academic research	Open
FWPA LCI	LCI for timber products	FWPA	Emission/SI unit (kg, m^2 etc.)	<10	LCI (cradle-to gate)	Industry and academic research	Open
RAIA	EE for building products	RAIA**	MJ/SI unit (kg, m^2 etc.)	<100	Emb. E (cradle to gate)	Academic research	Open
Others	EE for building products	Various (mostly academic)	MJ/SI unit (kg, m^2 etc.)	<100	Emb. E (cradle to gate)	Academic research	Open

*Building Products Innovation Council

**Royal Architecture Institute for Australia

For New Zealand, Alcorn and Wood (1998) developed EE data for building materials using the process based hybrid analysis. Building products cover 30 items which include cement, concrete, earth, insulation, paper, timber and steel etc. These embodied data covers cradle-to gate (factory). Centre for Building Performance Research at VUW has developed comprehensive EE and CO_2 data for building production using hybrid method in New Zealand (Alcorn, 2003). This database covers more than 60 building products.

Table D4 Building products covered by New Zealand EEG database

Building product	Modules
Concrete	6
Steel	6
Aluminium	7
Aggregates	2
Glass product	2
Ceramic products	2
Plasterboard	2
Timber products	3
Paints	1
Insulation material	4
Others	13
Total	48

Source: Email communication (2013b)

D. 2 North America

- USA

US NREL developed US LCI database (892 unit processes) having different system boundaries (gate-to gate, cradle-to gate and cradle to grave). These are commonly used materials, products or processes in the US. Building material/products are not covered in this database. Recently, US DOE (2010) provides EG for major building assemblies (e.g., windows, exterior/interior walls, roof assemblies, floor structures and column and beam assemblies). These data are based on Athena Sustainable Materials Institute's tool (EcoCalculator), which covers full life cycle (extraction, processing, transportation, maintenance and replacement during 60 years and demolition including transportation to landfill site) based on process method (Table D5).

Table D5 EE and EG of building assemblies in the U.S.

Assemblies	Type	EE (MMBtu/ft^2)**	EG (lbs of CO$_{2eq}$/ft^2)**
Window	Aluminium	0.973	190.1
	PVC-clad wood	0.447	88.3
	Wood	0.435	90.9
	Vinyl (PVC)	0.557	111.7
	Curtain-wall viewable glazing	0.233	66.1
Studded exterior wall	Steel stud wall (5 types)*	0.1~0.24	7.69~38.65
	Wood stud wall (5 types) *	0.05~0.23	4.96~36.29
	Structural insulated pane (5 types)*	0.11~0.30	10.23~41.18
Concrete exterior wall	Concrete block (4 types) *	0.24~0.41	39.24~67.77
	Cast-in place concrete (4 types) *	0.11~0.28	21.08~49.60
	Concrete tilt-up (4 types) *	0.12~0.29	24.91~53.24
	Concrete form (4 types) *	0.14~0.30	27.03~54.63
Wood based roof	Glulam joist with plank decking (5 types)*	0.10~0.43	10.05~41.49
	Wood I-joist with WSP decking (5 types)*	0.09~0.42	9.11~40.54
	Solid wood joist with WSP decking (5 types)*	0.10~0.43	9.39~40.81
	Wood chord/steel web truss with WSP decking (5 types)*	0.11~0.44	13.10~44.53
	Wood truss (flat) WSP decking (5 types)*	0.09~0.42	9.72~41.16
	Wood truss with WSP decking (4 types)*	0.09~0.16	9.19~19.36
Roof	Precast hollow core concrete (5 types)*	0.11~0.44	20.24~51.68
	Precast double T (5 types)*	0.10~0.43	16.42~47.86
	Suspended concrete slab (5 types)*	0.18~0.51	36.33~48.04
	Open web steel joist, steel decking (5 types)*	0.12~0.45	14.29~45.72
Interior wall	Interior wall (9 types)*	0.21~0.21	2.84~34.02
Floor structure	Floor structure with interior ceiling finish of gypsum board (latex paint) (14 types)*	0.02~0.12	1.65~29.19

	Floor structure without interior ceiling finish (14 types)*	0.04~0.13	2.91~30.42
Column and Beam	Non load bearing exterior wall (10 types)*	0.016~0.101	0.49~17.57
	Load bearing exterior wall (10 types)*	0.013~0.070	1.12~13.49

* Ranged depending on the type
US Lowrise building with 60 years lifetime.
** EEG includes extraction, processing, transportation, construction and disposal of materials.

Carnegie Mellon University (Green Design Institute) developed web-based LCA tool in 2008 (EIO-LCA, www.eiolca.net) which is based on economic input output tables for different countries (US, Canada, Germany, Spain and China). This tool provides EEG for building and products with monetary based unit (e.g., t-CO$_{2eq}$/US\$1million). The data covers cradle to gate of construction industry sectors. Some example shows in Table D6. The data used for modelling are 2002 economic input output tables for US, Canada, Spain & China, and 1995 for Germany.

Table D6 Example of EG (t-CO$_{2eq}$/US\$1million) of products using EIO-LCA

Sector	**Total (t-CO$_{2eq}$)**	**CO2 Fossil (t-CO$_{2eq}$)**	**CO2 Process (t-CO$_{2eq}$)**	**CH4 (t-CO$_{2eq}$)**	**N2O (t-CO$_{2eq}$)**	**HFC/PFCs (t-CO$_{2eq}$)**
Brick, tile, and other structural clay product manufacturing	1350	1350	0	0	0	0
Cement manufacturing	10300	4310	6000	0	0	0
Concrete pipe, brick & block manufacturing	109	109	0	0	0	0
Iron and steel mills	64.1	24.2	39.5	0.39	0	0

- Minnesota Building Materials Database

University of Minnesota developed Minnesota Building Materials Database in 2003 (CSBR, 2003). The purpose of this database is to help selecting sustainable materials, which are locally produced in the Rocky Mountain region. Selected materials, the 6 environmental impact categories (Primary energy, solid waste, air pollution, water pollution, resource use and global warming potential) are evaluated for selected materials using Athena and BEES. The material covers 16 divisions as shown in Table D7. The data provides life cycle impact for cradle to grave building materials. Since the data are taken from Athena and BEES, thus the quantification approach would be process based. In the provided data, EE can be used from the fossil fuel depletion (MJ) and EG from global warming potential (g-CO$_{2eq}$) but the data can be generated from two different tools (Athena and BEES), the EEG data can be represented differently.

Table D7 Building materials covered in Minnesota Building Materials Database

Division	Group	Data
1	General	No data at this stage*
2	Site construction	No data at this stage*
3	Concrete	3 different type of concretes
4	Masonry	Concrete masonry units (7 type of units)
5	Metals	No data at this stage*
6	Wood & plastic	Wood partition framing & blocking, wood sheathing, I-joist and LSL, Glulam, Joists, etc
7	Thermal & moisture protection	Vertical waterproofing, vapour retarder, cellulose blown, fibreglass batt & blown, etc
8	Windows & doors	No data at this stage*
9	Finishes	Wall tile, floor tile, acoustical tile, cork, linoleum, rubber, interior paint etc
10	Specialties	No data at this stage*
11	Equipment	No data at this stage*
12	Furnishings	No data at this stage*
13	Special construction	No data at this stage*
14	Conveying systems	No data at this stage*
15	Mechanical	No data at this stage*
16	Electrical	No data at this stage*

Data is taken from website (http://www.buildingmaterials.umn.edu/materials.html) on 20 June, 2014

- Canada

For Canada, there is no direct EEG dataset for building materials. But Athena Institute developed comprehensive life cycle inventory data for building materials and products using the process method. These materials/products include in Table D8. The LCI data covers cradle to gate (factory) environmental inventory of materials. Also, Athena Institute developed tool (EcoCalculator), which can provide life cycle GHG data for building assemblies (commercial & residential). During 60 years life span, the tool provides GHG data for building assemblies. In this case, different from material level, it covers cradle to grave GHG data as shown in Table D8.

Table D8 Athena LCI database for building materials

Product/Material Group	Product number	Note
Concrete products	4 including ready mix concrete, concrete masonry unit, precast product and mortar.	Data developed in from 2004 to 2011 for US and Canadian industry data
Steel products	16 products including nails, screws, rebar, sheet etc.	Data developed in 2013.
Wood products	9 products including softwood lumber, plywood, OSB, LVL, Glulam etc.	Data developed in from 2011 to 2012.
Claddings	7 products including metal cladding, clay/concrete bricks, PVC siding etc.	Data developed in from 2005 to 2013
Insulation and barrier products	7 products including polyethylene vapour barrier, mineral wool, fibreglass etc.	Data developed in from 2010 to 2012
Paint products	Basic latex, solvent based and varnish	Data developed by 1999
Gypsum board products	5 products including regular, fire rated, moisture resistant, gypsum fiber board, and joint compound & paper tape	Developed 1997 and updated 2012
Roofing products	14 products including 3tab shingles, mineral roll roofing, clay tile, concrete tile etc.	-
Windows	6 products including unclad wood frame, PVC frame, aluminium frame, metal clad wood frame etc	Mostly data developed from 2013

Source: ASI(2013)

D. 3 Europe

- UK

University of Bath ((2011) created ‘Inventory of Carbon and Energy (ICE) data for building materials. The ICE database covers more than 200 materials under the 30 main material categories (e.g., cement, concrete, glass, timber, steel etc) in UK & Europe. These data were originally collected from publicly available secondary resources (journal, book, conference, etc). The data scope of system boundary is cradle to factory gate (such as extraction of raw materials, transport and process in the factory site) and used process based method for quantification. The ICE data provides EE as for MJ and kg-CO_{2eq} per mass based building materials. It can be freely downloaded from website (www.circularecology.com).

- Germany (Ökobau.dat)

Ökobau.dat is a German LCI database for building materials, which was developed as part of research projects (research initiative ZukunftBAU by the PE International AG) with support of the German construction industry. There are nine building material categories (Mineral building materials, Insulation materials, Wood products, Metals, Coatings & sealants, Construction of plastics, Components of windows/doors & curtain walling, Building and Others) with more than 1000 processes for building materials and construction and transport in the dataset (BBSR, 2014).

The data are created with process method and the system boundary is covered by cradle to gate (Factory). Original data are sourced from GaBi database.

- Switzerland (KBOB/eco-bau/IPB recommendation 2009/1:2014)

LCA data of building materials, building services, energy supply, transports and waste management developed for an application in Switzerland. The data cover 172 building products structured into 15 material groups (concrete, bricks, other solid materials, mortar & plaster, windows and façade systems, metals, wood and wooden materials, adhesives & sealants, membranes, insulation materials, flooring materials, doors, tubes, paint & coatings and plastics), 39 building services structured into 4 groups (heating systems, ventilation systems, sanitary systems and electrical systems), 80 energy supply systems structured into 6 groups (fuels, district heat, useful heat, useful heat produced on-site (with solar collectors and heat pumps), electricity, electricity generated on-site), 56 transport services structured into 4 groups (fuels, freight transports, passenger transports per km, passenger transports per pkm), and 102 waste management processes structured into two groups (waste management of building materials and waste management of building services). The data provided cumulative energy demand in MJ (total and non renewable, also called EE), greenhouse gas emissions in kg CO_{2eq} assessed with IPCC 2013, (also called EG) and total environmental impacts in ecopoints assessed with the eco-factors 2013 of the ecological scarcity method. The data of building materials and building services cover cradle to gate plus waste management, thus excluding their use phase. The data can be downloaded from the eco-bau website (http://www.eco-bau.ch/index.cfm?Nav=20&js=1). All background information and data are transparently reported and available on a unit process level.

- France (DIOGEN)

French Association of Civil Engineering (AFGC) developed LCI data for civil works. The covered data includes steels (steel, reinforcing steel etc), wood (gross siding softwood, plywood, battens, glulam, beam etc), concrete (different type of concretes), other components (aggregates, recycled aggregates, etc). The data provides total energy consumption and greenhouse gas emissions (kg-CO_{2eq}) for various building materials emitted from cradle to gate (factory). The data was originally sourced from ecoinvent database. For more details can be found in the website (http://www.diogen.fr/).

Appendix E Example quantification

Table E1 Simple calculation sheet (initial embodied impacts)

Item	**Name of materials and equipment**	**Quantity**	**Unit**	**EE Intensity**	**EG Intensity**	**Initial EE**	**Initial EG**
				MJ/Unit	**kg-CO_{2eq}/unit**	**GJ**	**t-CO_{2eq}**
Building							
Structure	Concrete						
	Steel bars						
Outer wall finishing	Tiles						
	Metal window frames						
	Insulation						
	Fluorocarbon gases			▨	1,030 (R245fa)*	▨	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Lifts							
Site work	Temporary work, electricity bill						
Total							

*This is an example of EG intensity for R245fa. It varies depending on the type of Fluorocarbon gas used for cooling system

Table E2 Calculation Sheet (Lifecycle)

Item	**Materials and equipment**	**Initial EE**	**Initial EG**	**Maintenance**	**Number of Times Replaced**	**Demolition**	**Lifecycle EE**	**Lifecycle EG**
		GJ	t-CO_{2eq}				GJ	t-CO_{2eq}
Building								
Struc-ture	Concrete							
	Steel bars							
Outer wall finishing	Tiles							
	Metal window frames							
	Insulation							
	Fluorocarbon gases	▨		▨			▨	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
Lifts								
Site work	Temporary work, electricity bill							
Total								

Table E3 Densities of insulators, types of Fluorocarbon gases and their content rates

	Thermal conductivity W/(m·K)	Density kg/m^3	Type of Fluorocarbon	GWP (-)	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

Source: Fuji Research Institute, 1998.

Table E4 Emissions factor and collection rate at the time of disposal by refrigerator

Name of Equipment	Intensity of refrigerants [kg/3kWth]*	CO_2 emissions factor			Recovery efficiency
		IPCC Guideline (2006)	Japan**	Recommendation	Japan***
Chillers	1.0	2%-15%	6%-7%	3%	30%
Residential and commercial A/C including heat pump	1.0	1%-10%	2%-5%	2%	

*Japanese Gov. 2010, **Japanese Gov. 2009, ***Japanese Gov. 2013

Table E5 GWPs of individual refrigerants

Fluorocarbon gas	GWP
R410A	2090
R134a	1430
R32	675
R245fa	1030
HFO1234ez	6

Appendix F Preparing embodied impact intensities for example building

The embodied impact intensities of building materials for this Japanese case, were calculated based on Japanese 2005 national Input Output data. However, depending on the location of the building, the geographical boundary or the assessment tradition, impact intensities can be selected differently, in particular by using process based LCA data (see e.g. KBOB et al. 2014). EEG emissions for building materials, which were used for the example building are shown in Table F1.

Embodied intensity of machinery and equipment

Intensities of major equipment used in the construction sector, such as refrigerators, pumps and substations are shown in Table F1. These equipment fundamentally require number of sub components and parts and thus it makes it complicated to quantify the embodied impacts. The Embodied impacts can be obtained using the economic value by multiplying the purchase amount for each device and the monetary based embodied intensity as shown in below tables. Intensities of these devices are generally similar and the coefficient of variance (=Standard deviation/Average) is at the 10% level, which is relatively small in the Japanese case. The average values are 24,763 MJ/Million yen and 1,978 kg-CO_2/Million yen (Table F1). Unlike material quantity data, these intensities are available at the planning stage.

In terms of insulators (thermosetting resin), concrete, steel bars and lighting fixtures, intensities per unit may be obtained directly from the input-output table shown in Table F2. Energy and GHG emissions in this table is based on the consumer price. But it can be converted to physical quantity based using the quantity of materials per unit price (Million yen).

Table F1 EEG intensities (Extracts from 401 sectors)

No	Industrial No	Industrial Sector	Energy (MJ)	CO_2(kg-CO_2)	Unit/Mil. Yen
			Per Consumer price of Million Yen	Per Consumer price of Million Yen	Quantity of Material *for Consumer Price of Million Yen
1	30	Gravel and quarrying	52,153	3,626	287.5 t
2	31	Crushed stones	52,030	3,640	593.1 t
3	87	Timber	13,621	952	22.68 m^3
4	88	Plywood	22,697	1,599	7.0 m^3
5	120	Thermo-Setting resins	94,869	6,570	1.884 t
6	121	Thermoplastics resins	267,594	18,347	6.002 t
7	146	Sheet glass and safety glass	36,902	2,636	
8	147	Glass fibre and glass fibre products	71,691	4,842	
9	149	Cement	315,036	80,992	124.4 t
10	150	Ready mixed concrete	81,093	16,745	62.60 m^3
11	151	Cement products	43,193	5,994	
12	152	Ceramic	54,376	3,500	
13	162	Hot rolled steel	189,779	18,271	13.47 t
14	163	Steel pipes and tubes	119,963	11,182	6.158 t
15	165	Coated steel	90,489	7,958	9.002 t
16	175	Electric wires and cables	22,562	1,611	0.645 Conductor-t
17	182	Metal products for construction	63,388	5,577	
18	183	Metal products for architecture	35,353	2,878	
19	189	Boilers	22,980	1,832	
20	192	Conveyors	28,736	2,359	

21	193	Refrigerators and air conditioning apparatus	23,502	1,808	
Th2 2	194	Pumps and compressors	27,127	2,238	
23	215	Electric transformer	21,509	1,727	
24	216	Relay switches and switch boards	22,878	1,780	
25	223	Electric lighting fixtures and apparatus	24,345	1,770	284.3 p
26	226	Air conditioning equipment for consumer use	21,210	1,577	11.13 p
27	276	Residential construction（wooden）	19,921	1,707	6.318 m^2
28	277	Residential construction（non-wooden）	29,055	2,704	5.527 m^2
29	278	Non-residential construction（wooden）	21,103	1,835	7.749 m^2
30	279	Non-residential construction（non-wooden）	29,644	2,704	6.844 m^2
31	280	Repair of constructions	27,466	2,436	
32	375	Building maintenance services	7,753	548	
33	377	Civil engineering and construction services	11,234	801	

Source: Ashimura et al., 2010. * No single product manufactured.

*

Table F2 Intensities of other materials

Name	**No.**	**Industrial Sector**	**Energy (MJ) Per Consumer Price of Million Yen**	**CO_2(kg-CO_2) Per Consumer Price of Million Yen**
Tiles	152	Ceramic	54,376	3,500
Metal window frames	183	Metal products for architecture	35,353	2,878
Sanitary ware	152	Ceramic	54,376	3,500

Embodied intensity of other activities

For the site work, costs for temporary work, power and water at the time of construction are mostly proportional to the scale of the building, and can be represented by the gross floor area. Thus, as shown in Table F3, embodied intensities per gross floor area are used for site work. Table F4 shows embodied impact intensities obtained from the calculation results for two types of sample buildings.

Table F3 Embodied intensities of site work

	Energy (MJ/m^2)*	**CO_2(kg-CO_2/m^2)***
Site work	431	33

* averaged value taken from Table F4.

Table F4 Calculation results of sample buildings (site work)

	Purchase amount	Calculation Result		Per Gross Floor Area	
		Energy (MJ)	CO_2 (kg-CO_2)	Energy (MJ/m^2)	CO_2 (kg-CO_2/m^2)
Library (2,413m^2) (See Chapter 4)	31,836,970	1,158,480	81,494	480	34
Office Building (11,015m^2)*	221,101,460	4,207,002	365,180	382	33

*Yamamoto et al., 2015

In terms of interior finishing work, embodied impact intensities are also thought to be mostly proportional to the scale of the building. The intensities are shown in Table F5. Table F5 shows intensities of interior finishing work which were obtained for the two sample building types. The intensities shown in in Table F5 are the average values of the corresponding intensities shown in Table F6.

Table F5 Intensities of finishing work

	Energy (MJ/m^2)	**CO_2(kg-CO_2/m^2)**
Internal finishing work	733	59

Table F6 Calculation results of sample buildings (finishing work)

	Purchase amount	**Calculation Result**		**Per Gross Floor Area**	
		Energy (MJ)	**CO_2 (kg-CO_2)**	**Energy (MJ/m^2)**	**CO_2(kg-CO_2/m^2)**
Library (2,413m^2) (See Chapter 4)	50,248,773	1,620,819	135,457	672	56
Office Building (11,015m^2)*	191,391,959	8,749,653	692,112	794	63

*Yamamoto et al., 2015

Intensities per million yen of individual work other than the building frame are shown in Table F7. The intensities are similar to those of machinery and equipment. Costs for these engineering works are obtained by from data owned by individual countries and companies.

Table F7 Intensities of finishing work*

	Energy (MJ/million yen)	**CO_2 (kg-CO_2/million yen)**
Other work	26,500	2,100

Appendix G Results of simple calculation

Table G1 Result of Simple Calculation (Initial)

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	106Yen	54,376	3,500	241	15
	Metal window frames	13.256	106Yen	35,353	2,878	469	38
	Insulation	0.754	t	44,584	3,057	34	2
	Fluorocarbon gases	0	kg		1030		0
Internal finishing		2,413	m^2GFA	733	59	1,769	142
Other work for building		37.437	106Yen	26,500	2,100	992	79
Subtotal						8,845	1,038
Electric	Transformers	0.341	106Yen	21,509	1,727	7	1
	Switching boards	3.433	106Yen	22,878	1,780	79	6
	Lighting	557	Nos.	85.6	6.2	48	3
	Other work for electric	16.642	106Yen	26,500	2,100	441	35
Subtotal						575	45
HVAC	Chillers	8.440	106Yen	23,502	1,808	198	15
	Air conditioners	11.081	106Yen	23,502	1,808	260	20
	fluorocarbon gases	26	kg		2,090		54
	Other work for HVAC	24.800	106Yen	26,500	2,100	657	52
Subtotal						1,116	142
Plumbing	Sanitary ware	1.299	106Yen	54,376	3,500	71	5
	Other work for plumbing	9.665	106Yen	26,500	2,100	256	20
Subtotal						327	25
Lifts		6.300	106Yen	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 G2 Result of Simple Calculation (Lifecycle 60 years)

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 gases		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 gases		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

Appendix H The floor plan for the example houses

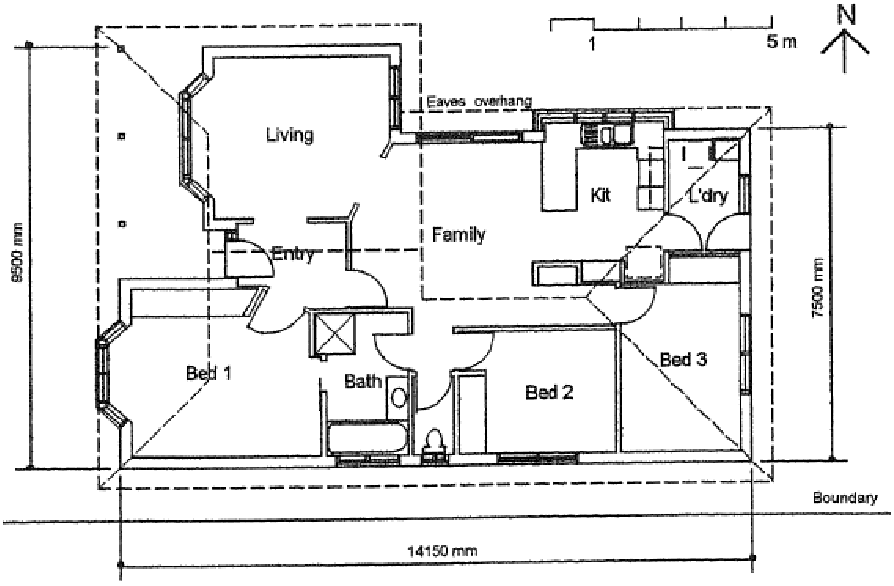
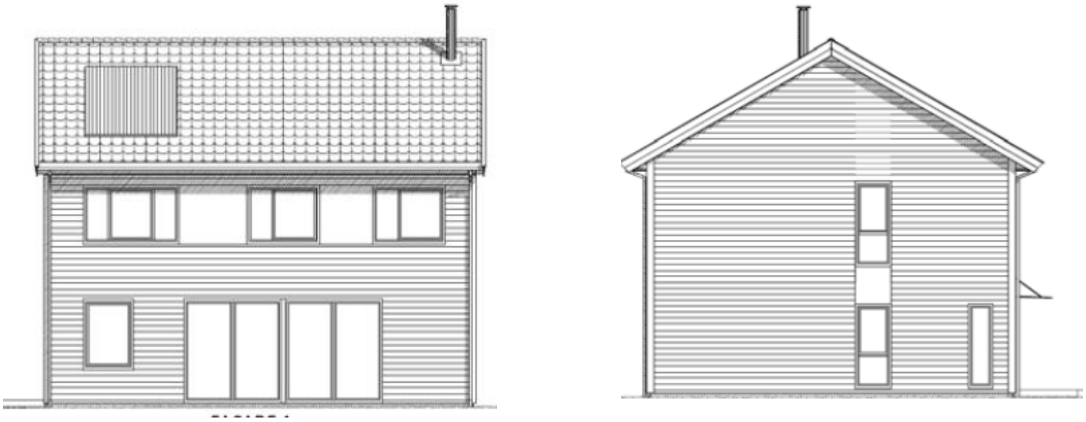
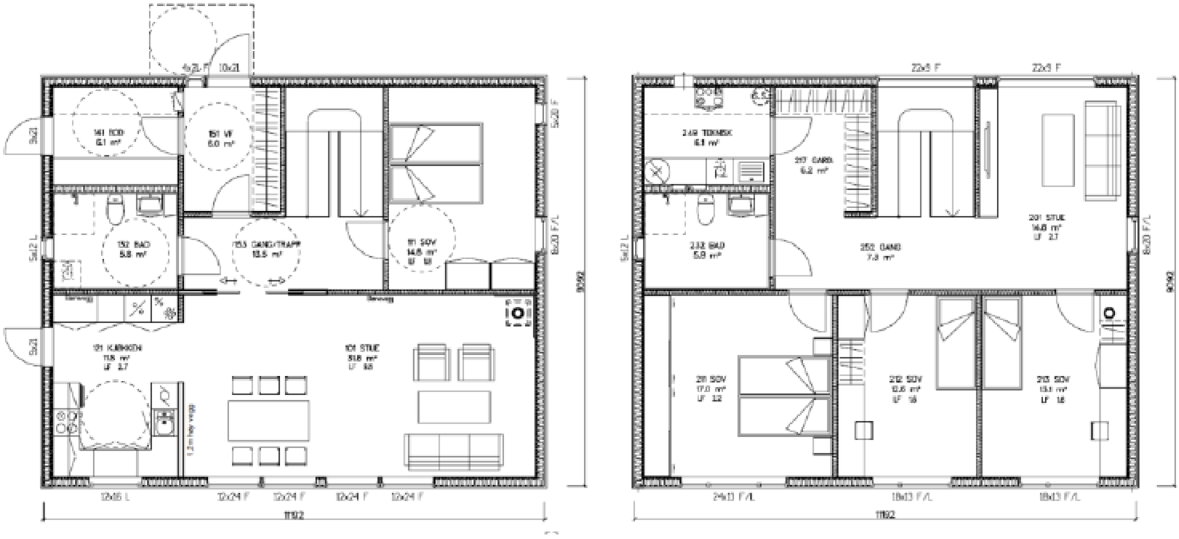


Figure H1. Floor plan of detached house in Australia (Fay, 1999)

Figure H2. Canadian detached house (Zhang et al., 2014)



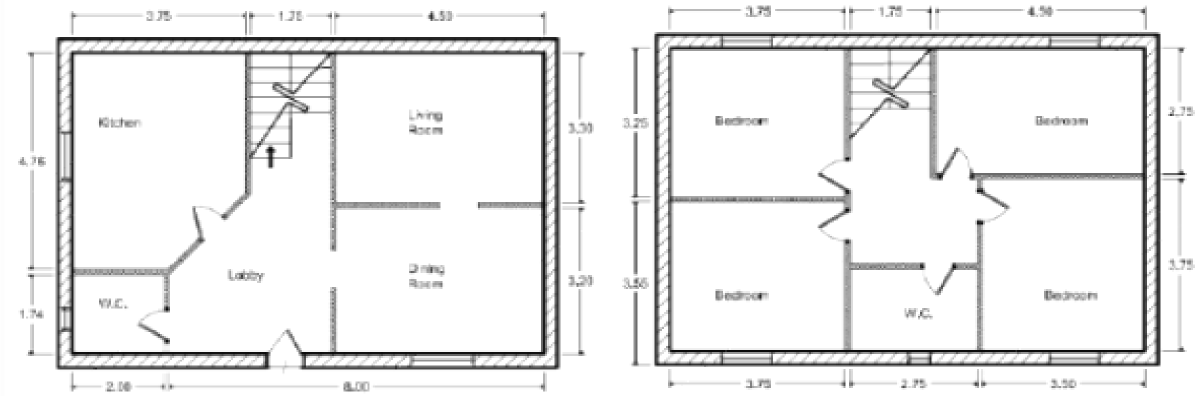
Façade of building



Ground floor

First floor

Figure H3. Norwegian typical residential building (floor plan, Dahlstrøm, 2011)



Ground floor

First floor

Figure H4. Floor plan for typical detached house in the UK (Franca, 2012)

Appendix I Recurring embodied energy impact

Study	**Building type**	**Life span**	**Relative impacts (%) for initial EE***
Treloar et al (2000)	Residential building	30	32%
Crawford et al. (2010)	Residential building assemblies Timber frame (concrete roof tile)	50	53%
	Timber frame (steel roof)	50	58%
	Timber frame (polystyrene)	50	116%
	Timber frame (brick veneer)	50	47%
	Steel frame (brick veneer)	50	44%
	Timber weatherboard	50	112%
	Concrete slab on ground	50	7%
Cole and Kernan (1996)	Office building (wood structure)	50	139%
	Office building (concrete structure)	50	128%
	Office building (steel structure)	50	135%
Fay et al. (2000)	Residential building	50	67%
	Residential building	75	113%
	Residential building	100	151%
Rauf and Crawford (2014)	Residential building (multi storey) with minimum life span of material	50	106%
	Residential building (multi storey) with average life span of material	50	44%
	Residential building (multi storey) with maximum life span of material	50	25%

*initial EE (=100%)

Appendix J Current trend of uses for refrigerants

Table J1 Trends of refrigerants

Example		**Developed country (Average weight, GWP)**	**Developing country (Average weight, GWP)**
Type, amounts and GWP of refrigerants for each equipment	Domestic	HC-600a (isobutene) and HFC-134a	HC-600a, HFC-134a And R22,,
	Commercial	HFC-134a, R-404A, R-407F and R-407A	R22, R-410A, HFC-134a, etc.
	Multi-type AC	R-407C, R-410A, and HFC-134a	R-407C, R-410A, HFC-134a and R22
	Refrigerator	R-407C, R-410A, and HFC-134a	HFC-134a and R22
Production situation	CFC HCFC	CFC is already banned. HCFC for new products is banned in 2010. In 2020, all HCFC will be banned.	CFC is banned in 2010. HCFC will be banned in 2030.
	R404	In EU, there is the plan to ban.	-
Plan to shift the type of refrigerants		<A/C> R22 → R-444B, R410A → HC-290, R-446A, R-447A, R-444B, R32(675), etc. <Refrigerator> HFC-134a → HFC-1234yf, HFC-1234ze R22 → R-410A, HFC-134a, R-407C, HC-290, etc.	

Source: UNEP (2015)

Appendix K Example of release/leakage of fluorocarbons

Table K1 Densities of insulators, types of Freon gases and their content rates

	Type of Freon	GWP (-)	Content rate (%)*
Expanded polystyrene	HFC-134a	1,430	2.7
Urethane foam (board-shaped)	HFC-245fa	1,030	4.7
Urethane foam (foamed on-site)	HFC-245fa	1,030	7.3

* % of total weight of insulator
NEDO (1999)

Table K2 shows the thermal conductivity, density, and content rate of each insulation materials containing fluorocarbon gases (NEDO, 1999).

Table K2 Specification of insulation materials

	Thermal Conductivity W/m/K	Density kg/m^3	Type of fluorocarbon gases	GWP	Content rate (%)
Expanded polystyrene	0.034	29	HFC-134a	1430	2.7
Urethane foam (board-shaped)	0.028	30	HFC-245fa	1030	4.7
Urethane foam (foamed on-site)	0.028	30	HFC-245fa	1030	7.3

Source: NEDO (1999)

Condition

As shown in Table K3, ordinary specifications use R245fa as the insulation material's foaming agent and R410A as the refrigerants for the air conditioner. On the other hand, the low environmental load-compatible specification uses CO_2 as the insulation material's foaming agent and R32 as the refrigerants for the air conditioner.

Table K3 Condition of example case of release/leakage of fluorocarbons

Condition	Form blowing agent for insulation material	Refrigerant of Air conditioner
Conventional	R-245fa	R410A
Low impact	CO_2	R32

In the case of R32 refrigerant, split types for connecting one indoor unit to one outdoor unit have already been placed on the market, while multi-split types for several indoor units connected to one outdoor unit are still under development. For the amount of refrigerant sealed in this multi-split type, the expected values were obtained from the manufacturer.

Table K4 A/C list in example building

No.	Equipment	Capacity	Quantity	Amount of refrigerant kg	
				R410A	R32
1	Air cooled multi type heat pump air Conditioner (outdoor unit)	Cooling ; 73.0ｋW Heating ; 81.5kW	3	19.4	13.6
2	Air cooled multi type heat pump air Conditioner (outdoor unit)	Cooling ; 67.4ｋW Heating ; 75.0kW	11	16.8	11.8
3	Air cooled multi type heat pump air Conditioner (indoor unit)	Cooling ; 7.1ｋW Heating ; 8.0kW	33	-	-
4	Air cooled multi type heat pump air Conditioner (indoor unit)	Cooling ; 11.2ｋW Heating ; 12.5kW	42	-	-
5	Air cooled multi type heat pump air Conditioner (indoor unit)	Cooling ; 9.0ｋW Heating ; 10.0kW	9	-	-
6	Air cooled heat pump air conditioner	Cooling ; 4.0ｋW Heating ; 5.2kW	2	1.2	1.02
7	Air cooled heat pump air conditioner	Cooling ; 8.0ｋW Heating ; 10.8kW	1	3.2	2.72
Total		Cooling ; 976ｋW Heating ; 1091kW		444	311

Note1; The amount of refrigerator is at the time of delivery.
Note2; The amount of refrigerator is included the amount of additional refrigerator for pipe length of building.

Table K5 Insulation materials used in example building

Part	Material	Specifications	Area m²	Weight kg	Content rate %	Contents kg
Roof-top	Urethane foam	25kg/m³, 20t	44	22	4.7	1.0
Roof-top	Urethane foam	25kg/m³, 25t	660	413	4.7	19.4
Wall/ceiling, etc.	Urethane spray	25kg/m³, 15t	2027	760	7.3	55.5
Total				674		75.9

Table K6 Initial cost of building elements

Work item	amount JPY	per gross floor area (JPY/m²)
Building	924,395,544	124,589
Electricity	175,595,290	23,667
Air conditioning	168,057,613	22,651
Plumbing & Sanitary	51,295,662	6,914
Lift	143,173,258	19,297
Total	1,462,517,367	197,117

Calculation

The rate of refrigerant leaks was assumed to be 2%/year from Table 17 and, the rate of recovery at the time of equipment abandonment, 30% (70% leaks) from the same table. The amount of fluorocarbon gas was determined, assuming the insulation material takes the value in Table K2 as its content rate of the gas (Table K5). In this case, the effects of the fluorocarbon gas contained in heat insulation material were counted at the initial construction stage.

For the example building, GHG intensity is applied, which was obtained from Japanese IO analysis. Figure 20 shows the result of EG emissions between when considered fluorocarbons 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).

Appendix L Embodied impacts incorporating the effect of steel product recycling

For quantification of GHG emissions of steel, World Steel Association (WSA, 2011) proposes a methodology based on the End of Life (EoL) Approach. This approach assumed that steel products are suitable for horizontal recycling, and thus GHG emissions due to manufacture of a steel are redistributed to the next-generation product, thereby levelling the environmental impact (GHG) imposed at the production stage. That is, when assessing environmental impacts of steel products, it is a comprehensive approach that eliminates the distinction between products to be produced by melting iron ore (blast furnace products) and products to be produced primarily by melting scrap (electric arc furnace products). Figure A1 shows the concept of WSA's comprehensive approach.

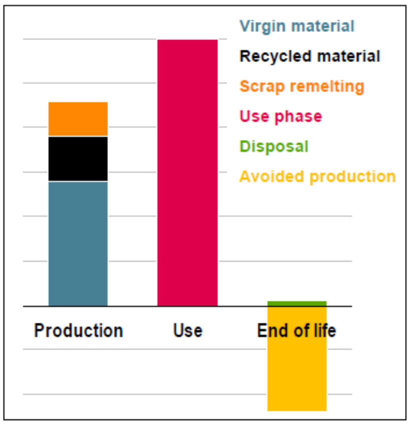


Figure L1. Concept of End-of-Life Approach (WSA, 2011)

L. 1 Relation between the Blast Furnace Method and the Electric Arc Furnace Method in the Production of Iron and Steel Products

Two methods are used in iron- and steelmaking: the blast furnace (BF) method and the electric arc furnace (EAF) method. The BF method denotes a process in which pig iron (molten iron) that is produced in a blast furnace, using iron ore as the main raw material, is then refined in a basic oxygen furnace to produce steel. The EAF method denotes a process in which used steel materials are re-melted typically in an electric arc furnace to produce steel, or in which scrap steel is converted into renewed steel in an electric arc furnace.

Figure L2 shows the relation between the BF method and the EAF method. As shown in the figure, iron ore is not the only material used as a raw material in the BF method, and the materials applied in the EAF method are not restricted to scrap steel. For example, it is common in the BF method to use scrap steel (amounting to about 10~20% of the total load of raw materials used as iron sources), and there are cases in which reduced iron is used as a source material in the EF method (refer to Figure L3). That is, it can be understood that both the BF and EAF methods can be used rationally to produce iron and steel products.

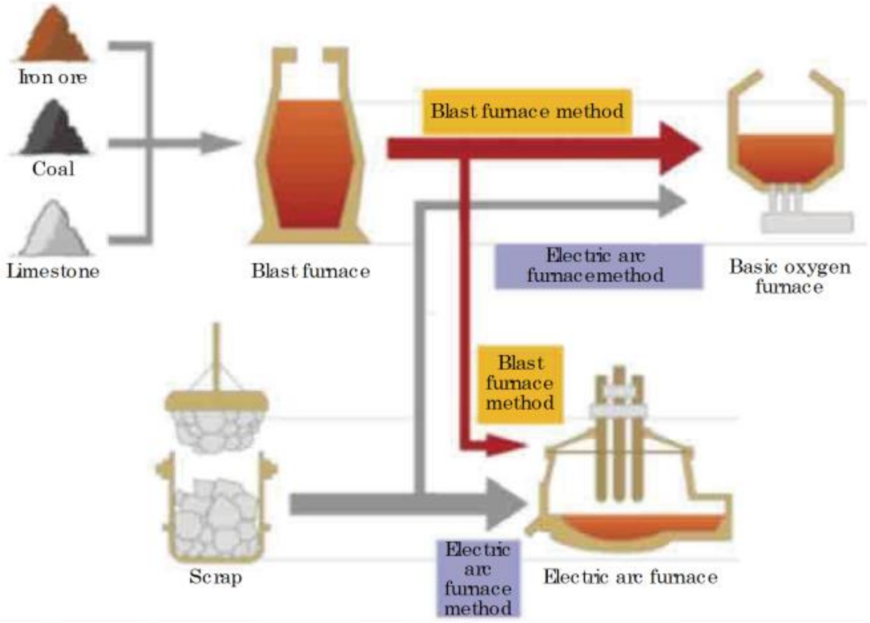


Figure L2. Relation between BF Method and EAF Method

L. 2 Calculation Method for LCIEoL That Takes Recycling Effects into Account

L.2.1 External Scrap LCI

In calculating LCI_{EoL}, the LCI of External Scrap (scrap LCI) is conceived as corresponding to this statement: "Y kg of steel product is produced from 1 kg of External Scrap employing the EAF method, and this scrap LCI take overs Y kg worth of LCI of steel product produced employing the BF method." Y indicates the production efficiency (yield) at the stage when steel products employing the EAF method are produced. When the LCI of steel products produced by the EAF method (theoretical value assuming 100% use of External Scrap) is defined as Xre, and the LCI of steel products produced by the BF method (theoretical value assuming 0% use of External Scrap) is defined as X_{pr}, the scrap LCI can be defined as follows.

$$Scrap\ LCI = X_{pr} \cdot Y - X_{re} \cdot Y = (X_{pr} - X_{re}) \cdot Y \tag{L1}$$

L.2.2 Calculation Equation for LCI_{EoL}

The LCI_{EoL} of steel products can be conceived as the total LCI obtained by deducting the scrap LCI-according to the External Scrap recovery rate (RR)--from the steel products LCI (X) that does not take account of recycling efficiency, and further adding (redistributing) the scrap LCI--according to the steel scrap application ratio (S)-during the production of steel products. When organizing the above, the following equation is obtained. The definition of each element used in the equation below is shown in Table 2.

$$LCI_{EoI} = X \ \ RR \cdot Scrap\ LCI + S \cdot Scrap\ LCI$$

From Equation (A1) (Scrap LCI=(Xpr–Xre)･Y),

$$LCI_{EoI} = X - (RR - S) \cdot (X_{pr} - X_{re}) \cdot Y$$

L.2.2.3 LCI Calculations That Fully Incorporate the High Recyclability of Steel Products

In the civil engineering and building construction area, the main approach to LCI is to assess the environmental impact imposed by steel products only from the stage of raw materials procurement and production to the point of their shipment (cradle to gate in other word), which is based on the life stage boundary shown in Figure A3. This approach does not assess emissions through the entire life of steel products. It is essential to employ an approach that takes the recycling effect (end of recycling, etc.) into account.

Currently, the Japan Iron and Steel Federation, under a tie-up with the World Steel Association, is promoting the incorporation into ISO standards of the above-mentioned approach to LCI calculations that takes the recycling effect into account. Further, in accordance with this approach to LCI calculation, we are promoting the calculation of LCI values for specific steel products based on production data collected by participating companies and employing this LCI calculation approach. The specific LCI values calculated for each product are targeted for public release in March 2016.

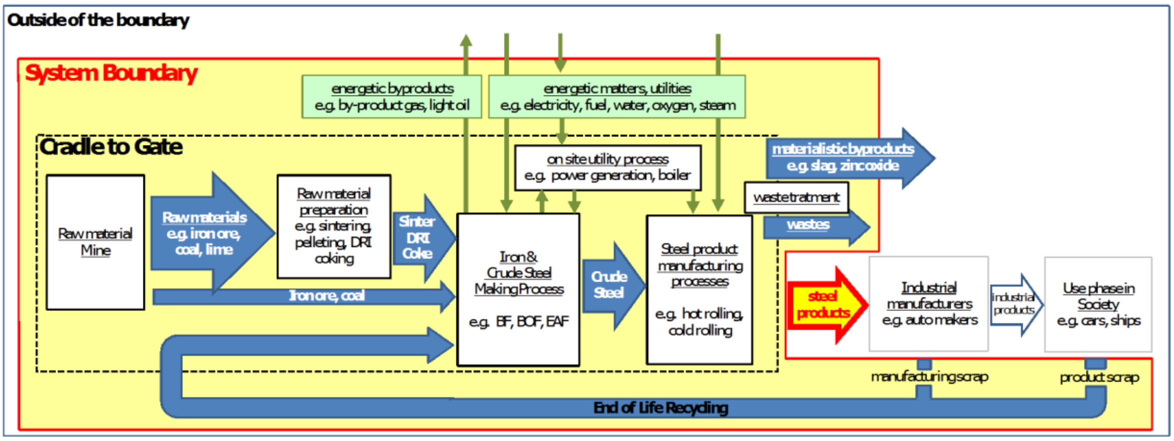


Figure L3. **System boundary for LCI calculation of steel products with EoL recycling**

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