International Energy Agency

Energy Conservation in Buildings and Community Systems Programme (Annex 57)

Subtask 2: Evaluation of Embodied Energy & Embodied GHG Emissions for Building Construction : A Literature Review

August 2016

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

Energy in Buildings and Communities Programme

International Energy Agency

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August 2016

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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 (*) 5

Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)

Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior Simulation
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70:Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Executive Summary

In the past, environmental impacts from building operation were the only issue to evaluate the environmental performance of building. More and more awareness of embodied energy/GHGs, however, has been increased among environmental professionals, companies or other stakeholders as measurements to evaluate environmental impacts from building construction activities since 90s. The ST2 report provides the results of literature review to find out any relation between subjects and calculation methods, which aims to support with more concrete foundation to Annex57's guidelines.

In order to carry out review tasks, ST2 investigated publications published between 1990 and 2013, using the keywords "Embodied Energy", "Embodied GHGs" and "CO_2" via the *Science Direct* website, where approximately 250 papers were selected and analysed in depth which related on "building" and "building related". The analysis is based on research trends by year, region, subject and influence range of environmental impacts, and the methodology, calculation method, and database used in each paper were examined at building material level, building component level, and building level.

Small number of studies of Embodied Energy and Embodied GHGs in the field of buildings were carried out in 1990. From 2000's, research focused on energy consumption started to use I-O LCA and Hybrid LCA methodology, and the study of embodied energy and GHGs utilizing Process-based LCA was carried out by a few countries. However, the study of embodied energy/GHGs increased explosively since 2007, such as Multi-regional I-O LCA and Environmental I-O LCA, a variety of methodologies have been introduced.

The research on building embodied energy/GHGs is not only dealt in particular region but rather a general topic of interest in various regions and countries including Europe, Asia and US. It is not only limited to the building but also covers a wide range of studies to building materials and component. This result implies that building experts consider the direct or indirect impacts of building material production and building activities as well as energy use in assessing the environmental impact of buildings.

Through the analysis results of the evaluation methods and data utilization, researchers have set different range of system boundaries, research period of assessment, and calculation parameters depend on their study purpose, and every methodology has its own advantages and limitations so it is very hard to suggest the one superior and suitable methodology to assess embodied energy/GHGs.

The result of ST2 confirms that the interest of the building's embodied energy/GHGs reaffirms the necessity of IEA EBC Annex 57 and that there are various ways to evaluate the building's embodied energy/GHGs. It was confirmed that in order to evaluate the inherent influence in the building life cycle, appropriate calculation methods including system boundary, assessment period and calculation parameters are presented. Therefore, guidelines by ST1, 3 and 4 will be a clear framework for embodied energy/GHGs assessment on building’s lifecycle in order to compare and understand various results by different environmental professionals and stakeholders.

Table of Contents

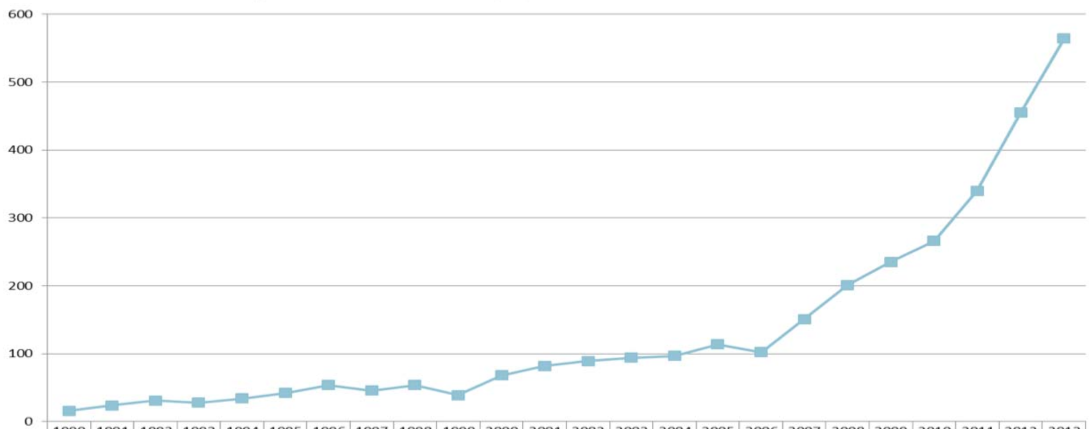
List of Figures

List of Tables

1. Overview and Boundary Conditions

The LCA technique has been widely used in the building sector since 1990 in order to find out the efficient way to achieve sustainable practices for green building. Applying LCA in the building sector, however, has become a distinct working area within LCA practice because building's life cycle has unique characteristics comparing to products from other industrial sectors. For instance, buildings have long lifetimes at least more than 50 years so it is difficult to predict occupants'behavior pattern of energy use or maintenance activities during building operation and its environmental impacts as the results. Although dividing building's life cycle of building into 4 stages, which are material production, construction, use and maintenance, and end-of-life, as defined in many authoritative international guidelines, has reached an agreement among LCA experts in building sector, still there is a great diversity of opinion concerning field data collection, scope of parameters, calculation and simulation method, and source of LCI DB. Furthermore, many stakeholders including policy-makers, building designers, construction companies and material manufacturers, are related in the building industry so that it is hard for each stakeholder to make a decision in order to minimize the environmental load from the life cycle perspective because of the lack of their understanding on the other stakeholder's role.

For these reasons, it is meaningful to perform literature review by Annex57 before suggesting evaluation method of embodied energy and embodied GHGs (EEG is the abbreviation for embodied energy and embodied GHGs in this chapter) from building's lifecycle. Literature materials were collected through the website of *ScienceDirect*[1] and searched under the keywords "Embodied energy", "Embodied GHGs" and "CO_2", which is the main subjects of this guideline. Total 3,822 of books, journals and papers were published from 1990 to 2013. As shown in the figure 1, the interest in embodied energy and GHGs emissions in various sector, not only building sector but also energy and industrial sectors, has been grown drastically since 2006. The recent publish rate is as much as everyday publishing more than 1.5 paper in worldwide. Only approximately 250 literature among them, however, were selected as reference for in-depth analysis after considering relation with building and construction sector. The analysis of reference studies is included from research trends in chronological sequence, LCA methodologies, LCI database, EEG calculation of different building types as well as components.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
papers	16	24	31	28	34	42	54	46	54	39	68	82	89	94	97	114	102	151	201	235	266	340	455	564

Figure 1. Number of published literature in embodied energy /GHGs study

1http://www.sciencedirect.com/, accessed 22 April, 2014

This chapter will give an overall understanding of existing LCA studies in the world since 1990s. The first part of this chapter will give an overview of LCA research trends by regions, subjects and influence range of environmental impacts. Second part will present various approaches towards embodied energy and embodied GHGs calculation in different level of building parts such as material level, component level and building level. Third part will attempt to provide significant findings, which summarize representative LCA methodologies and widely applied LCI database and calculation tools. Also it will discuss the limitations and improvement points of each methodology in order to be applied for embodied energy/GHGs assessment. And finally, this chapter will recommend the direction of developing evaluation guideline should proceed.

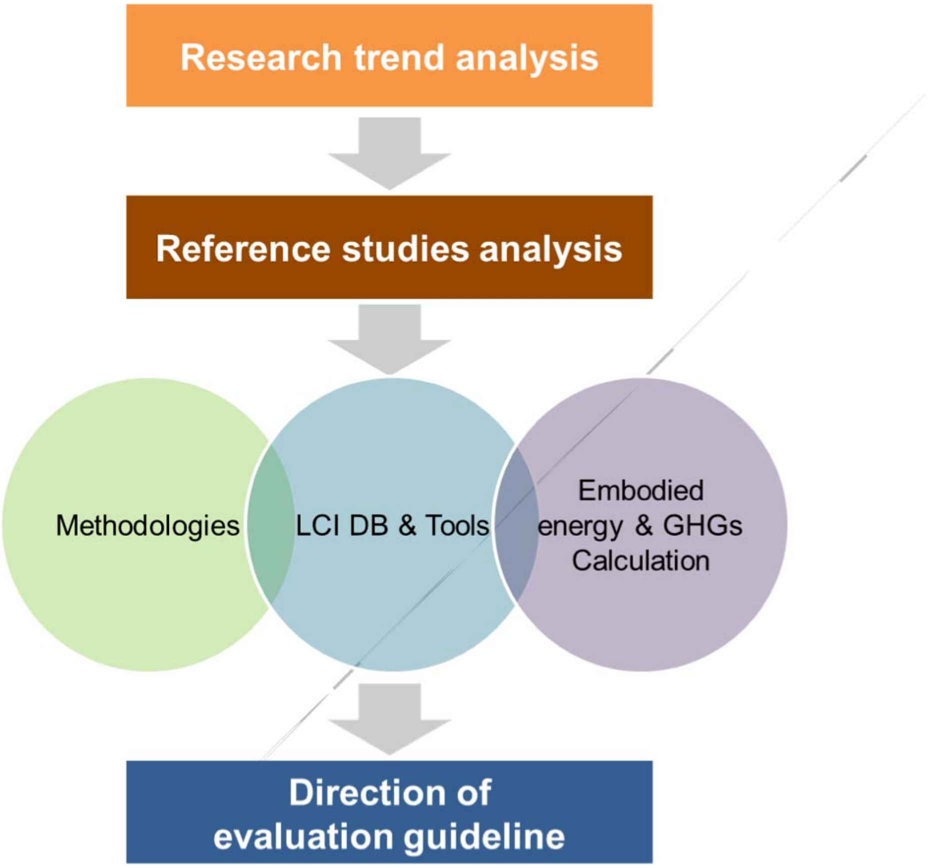


Figure 2. Overview of literature review

2. Current State of Research

2.1 Research trends by year

Only a few papers studied on building's embodied energy and its impact were found in the '90s. Some paper tried to study methodological comparison between Embodied energy analysis and Emergy analysis, which is a quantitative analysis technique for determining the values of resources, services and commodities (Brown *et al*, 1996). Primary energy and GHGs embodiments in goods and service in Austria was analyzed using I-O LCA method (Lenzen, 1998). Also there were several attempts to analyze energy and GHGs associated with the building materials or construction activities.

By the year 2006, embodied energy and GHGs study had been published gradually but slightly. Research themes, however, were diversified after the 20's, though the topics were still focused on energy consumption. In building level, the subjects were building materials, structure, envelope, energy related installation such as BIPV or low-energy building technology. In national or industrial level, several papers studied on energy consumption and GHG emissions impacts from the socio-economic point of view in order to be used for political decision. The dominant methodologies were I-O LCA and hybrid LCA to analyze the embodied impacts for not only in building level, but also national level study. Only in a few researches, Process based LCA was applied for evaluating embodied energy and GHGs in building level. Interestingly, a calculation frame work to estimate energy footprints was suggested according to the primary energies embodied in the goods and services consumed by a defined human population (Ferng, 2002).

There has been an explosive increase in the embodied energy and GHGs research after the year 2007. The methodological diversity has been found in every level of research scale. More researches have utilized Process based LCA methodology than before. Other special methodologies have been suggested such as multi-region I-O LCA (Wiedman, 2007), Environmental I-O LCA (Chen, 2010), quasi-multi-regional input–output (QMRIO) model (Druckman, 2009) and WRI/WBCSD GHG Protocol (Ozawa-Meida, 2011).

2.2 Research trends by regions

Considering the publish rate of literature by region, the most of studies on the embodied impacts in building and construction industry have been worked in progress in European and Asian countries. As shown inthe fig 3, Europe and Asia each accounts for around 43% and America accounts only for 14%. Among Asian countries, over half of literature has been published in China. The other leading country in the field of embodied impacts is UK and USA.

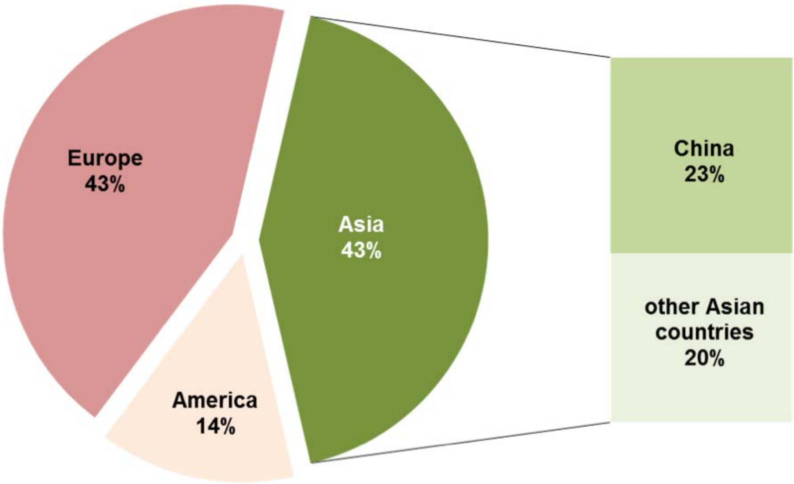


Figure 3. Published literature by region

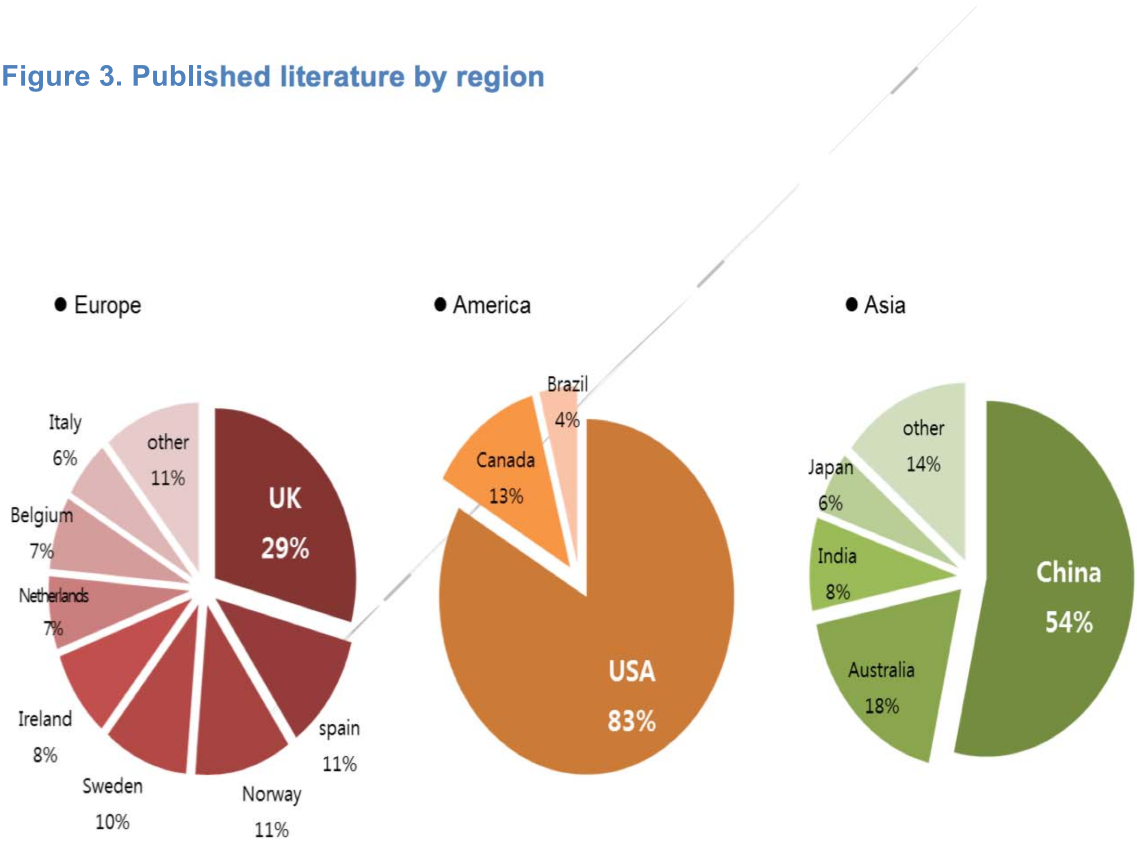


Figure 4. Published literature by countries

2.3 Research trends by subjects

The almost half of studied subjects are in building sector, and the main research topics are buildings including commercial buildings, educational facilities and hotels which comprise 57% of building sector.

The other half of subjects are embodied energy in international trade (18%), certifications and policies study (12%), environmental load from economic sector (12%) and embodied impacts by energy source change (9%).

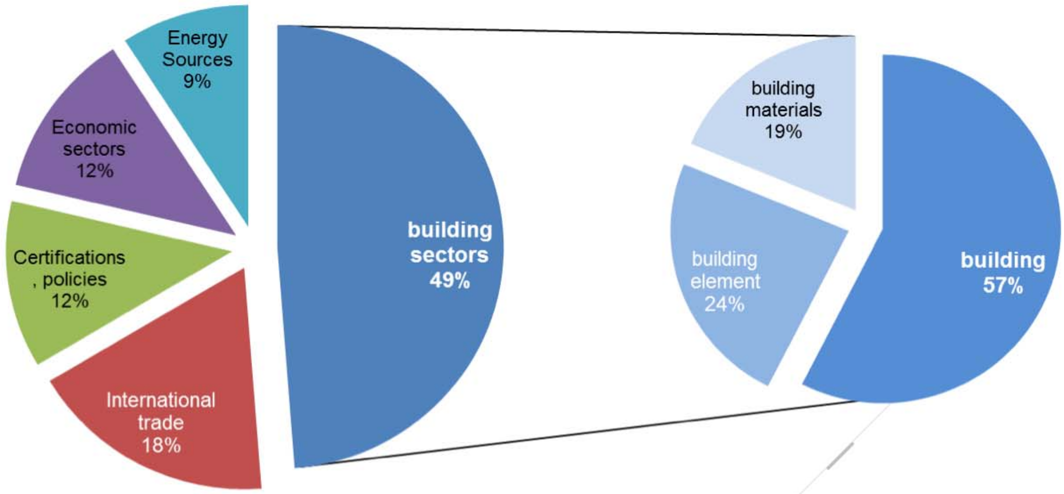


Figure 5. Research subjects in embodied energy and GHGs study

The embodied impacts studies in building sector have been shown a tendency of focusing mainly on comparing building with different structural materials, energy-efficient installations or various construction methods. The main topics in impacts from international trade have been selected to evaluate the direct and indirect impacts by using fossil fuels or to predict carbon tariffs on foreign products for protecting domestic industrial competitiveness. The motivation of embodied impacts studies in certifications or policies has been to evaluate embodied and operational energy savings by specific rating system, building energy regulations or certification schemes. The objective of embodied impacts study in economic sector has been aimed to assess sectorial embodiment intensity by consuming natural resources such as direct, indirect and primary energy. The research of embodied impacts in energy source field has been focused not only on environmental benefits from renewable energy source, but also on embodied exergy ecological footprint (EEEF) which illustrates the ecological overshoot of the general ecological system.

2.4 Research trends by influence range of environmental impacts

Evaluation parameters and calculation method can vary not only with the purpose of evaluation result application but also with the consideration of influential range of environmental impacts from subjects. Therefore, the research materials were analyzed on 3 different level of environmental influence; global impacts, national impacts and local impacts.

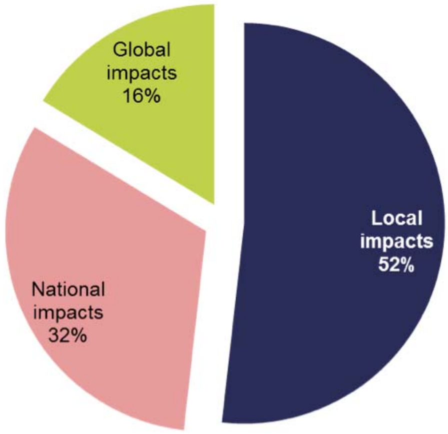


Figure 6. Influential range of environmental impacts

2.4.1 Local Impacts

More than half of the studies have been considered local environmental influence. The main subjects are embodied energy consumption and environmental impacts from buildings (48%), elements (27%) and materials (14%) which comprise 89% of all the research subjects. Process based LCA is the most applied methodology which accounted for 66%. The invented LCA methodologies (15%), such as WRI/WBCSD GHG Protocol, material & energy balance, building rating methods or questionnaire methods, are also quite applied to analyze local environmental influence. I-O LCA (3%) and hybrid I-O LCA (2%), however, show the tendency to be underutilized than Process based LCA. The stakeholders of the researches are mostly building designers (81%) and manufacturer (15%) which comprises 96% of all stakeholders group.

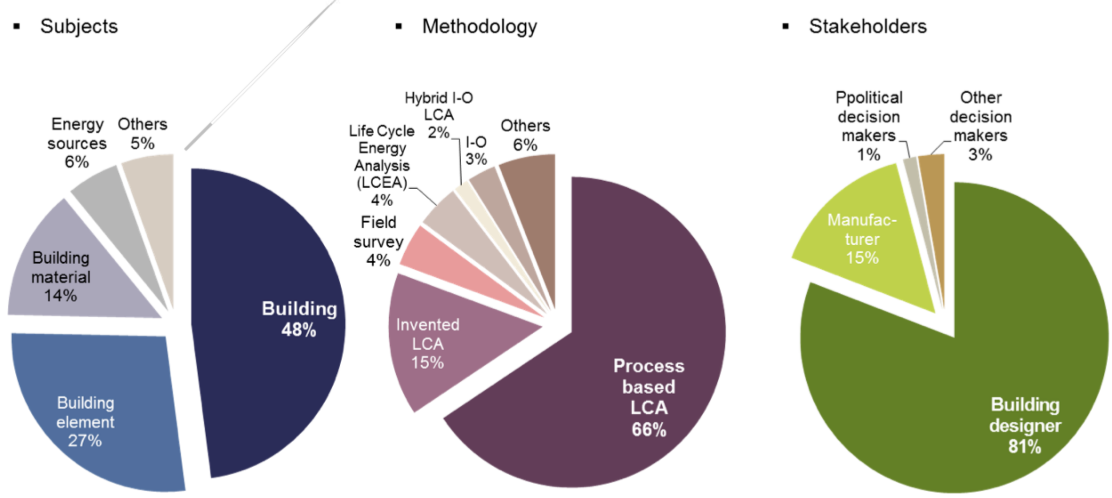


Figure 7. Research trend of EEG in local influence

2.4.2 National Impacts

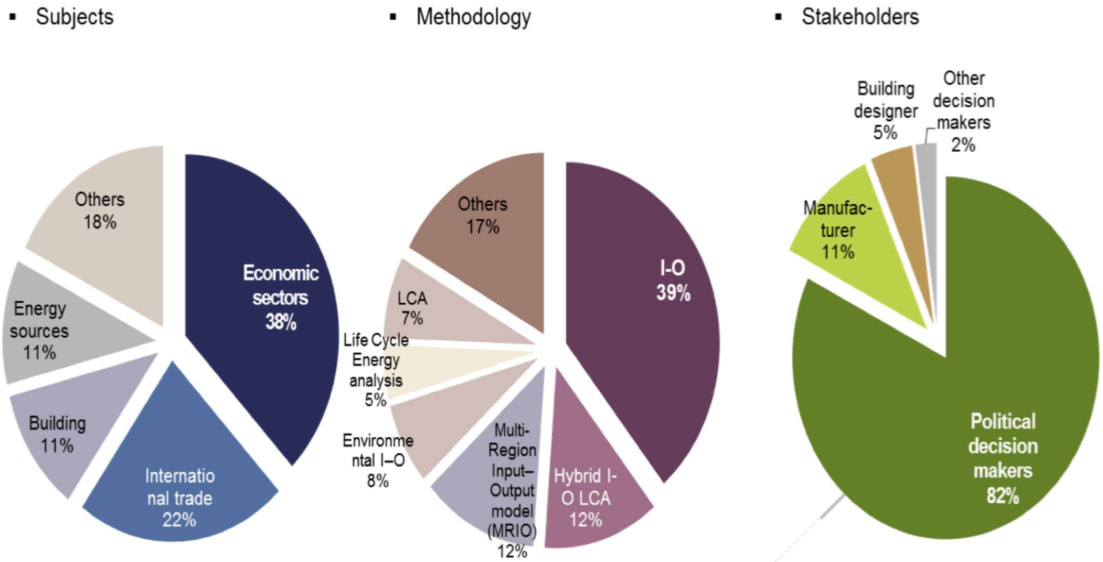


Figure 8.Research trend of EEG in national influence

About 32% of the studies have been considered national scale of environmental influence. More than half of the subjects range over economic sectors (38%) and international trade (22%). The research topics from building (11%) and energy sources (11%) comprise only 22%. National influence is evaluated in various ways, but more than 70% of methodologies are based on I-O LCA such as I-O (39%), hybrid I-O (12%), MRIO(multi-regional I-O) (12%), environmental I-O (8%). Other methodologies apply green building scheme, Consumer Lifestyle Approach (CLA) method, IPCC or ecological footprint to evaluate. Process base LCA is never used to national scale evaluation. The stakeholders of the researches are mostly political decision makers (82%) and manufacturer (11%) which comprises 93% of all stakeholders group.

2.4.3 Global Impacts

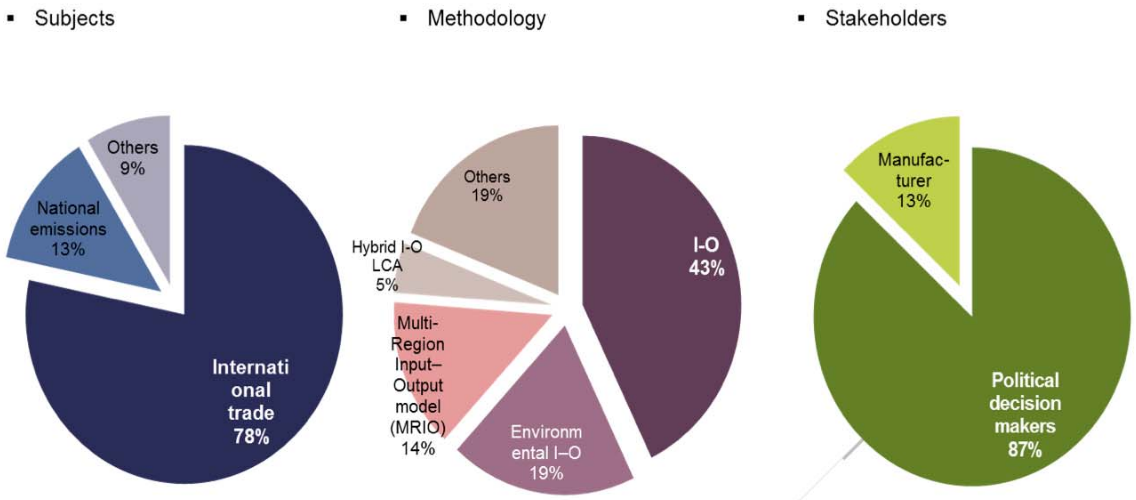


Figure 9. Research trend of EEG in global influence

About 36% of the studies have been considered global scale of environmental influence. 78% of the subjects are focused on the embodied energy consumption and GHG emissions from international trade. Other interesting topics in global influence are allocation responsibility of CO_2 emissions (Ferng, 2003), embodied CO_2 emissions of the world economy (Chen, 2010) and embodied energy in global manufacturing (KRA, 2010). Similar tendency to the national scale of influence, 81% of the evaluating methodologies are from I-O LCA. The stakeholders of the researches are comprised of political decision makers (87%) and manufacturer (13%).

3. Reference Studies Analysis

3.1 Building level

42 papers have been reviewed in relation to embodied energy/GHGs analysis in building level. The research subjects in the building level are mostly residential building, which comprises more than 80%. It is as in the following (given in Figure 10); low energy building (31%), residential detached house (27%), multi-story building (15%), apartment (11%), office (8%) and hotel (8%). Every paper has a tendency to include only environmental factors in embodied energy/GHGs analysis, while several researches consider economic factors together such as annual running cost (Monahan, 2010) or life cycle cost (Mithraratne*et al.*, 2004). Assessment periods of the reference studies are various from 1 year to 100 years. The most preferable assessment period is 50 years (47%) to analyze embodied impacts from a building's life cycle.

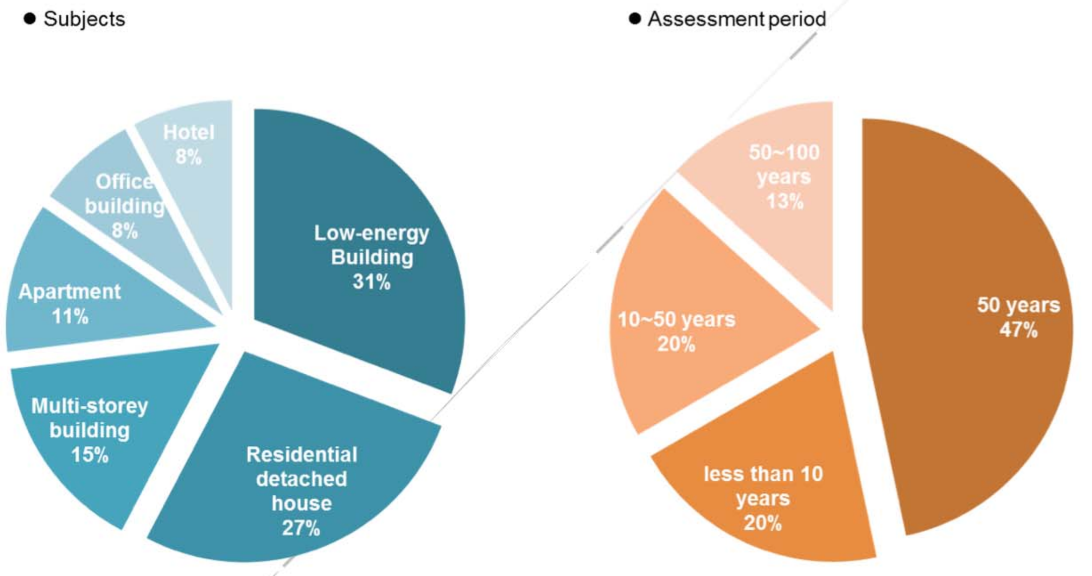


Figure 10.Research subjects and assessment period in building level

3.1.1 Methodology

Both process based LCA and I-O LCA methodologies are widely applied to evaluation in building level. As shown in the Table 1, case studies applied process based LCA have various assessment period from 1 year to long-term building's life cycle, while cases applied I-O LCA have at least 25 years of life cycle, in another words, the I-O methodology has an advantage over the projects with long evaluation period in building level.

In order to analyze the relation between research objectives and system boundary setting, environmental factors are classified into 4 categories: EE (Embodied Energy), EG (Embodied GHGs), OE (Operational Energy), and OG (Operational GHGs). Also system boundary are divided into 5 different stages as P (material production), T (material transportation to site), C (Construction), O (Building operation), and EOL (End of life). Literature review results show that there was no direct correlation between environmental factor selection and system boundary set-up. Due to absence of clear guideline to evaluate embodied energy/GHGs, researchers chose the environmental factors and set system boundary according to their objectives, so that it is impossible to compare between different case studies.

The most of assessments proceeded from production stage to building operation stage (43%). The reference flow was measured in m^2 or m^3. The results of embodied energy were expressed in MJ or Kwh unit, while that of embodied GHGs was commonly measured in GWP. More specific information related in system boundary and measurement can be found in the table 1 and 2.

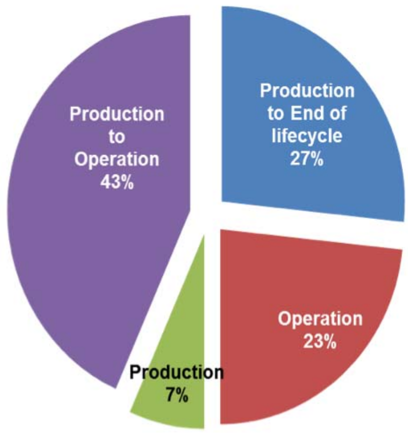


Figure 11. System boundary setting in building level

3.1.2 Calculation and Database

As showing in the figure 12, the most researchers have utilized energy data only (36%) or energy and building material data together (36%) for assessing embodied energy/GHGs in building's life cycle perspective. The rest of researchers have utilized certifications or design guidelines related in green building (14%) and market prices data of building materials (8%) to get calculation basis for embodied energy/GHGs. Few researchers have utilized building material data to calculate embodied energy/GHGs.

The most researchers have obtained data to calculate from field survey and monitoring (32%) and national statistics database (18%) such as BEDEC PR/PCT or DECC. Owing to lack of developed national average database, however, the papers published before year 2010 have showed a tendency to collect LCI database on embodied energy/GHGs from unspecified literature and to invent an evaluation tool for the researcher's own purpose. After becoming easier to access to national LCI database, more researchers have used domestic LCI database, which reflect the situation of domestic industry and life habit factors. Besides the national LCI DB, Ecoinvent, Bath ICE and BEES were also preferable database to obtain embodied energy consumption and equivalent GHGs emissions. SimaPRO, TCQ2000, ATHENA, and Equer software were used as LCA calculation tools. Interestingly, almost every research case has gathered operational data from both field survey method and energy simulation tools such as TRNSYS, Ecotect, ENORM ENSYST, Design builder, or eQUESTor ,rather than energy monitoring which was common before year 2010.

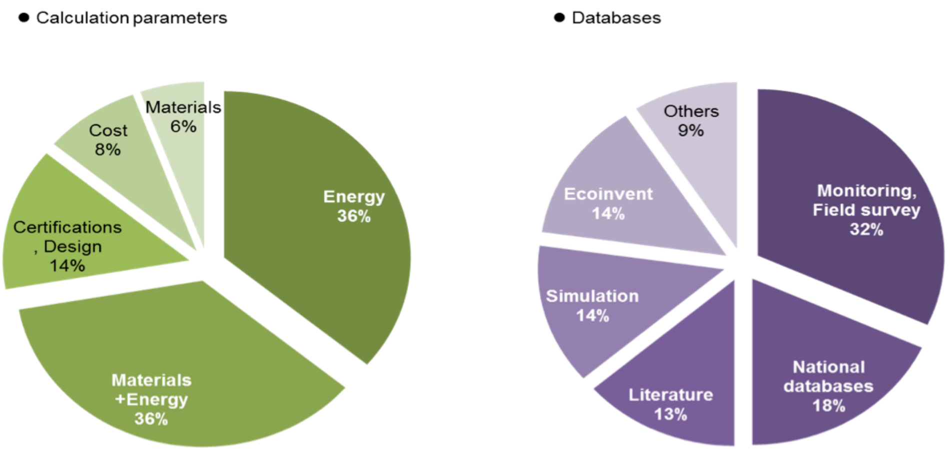


Figure 12. Calculation parameters and the source of LCI DB in building level

Table 1. Summary of reviewed case studies in building level (1)

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

*EE = Embodied energy, OE = Operational energy, EG = Embodied GHGs, OG = Operational GHGs

Table 2. Summary of reviewed case studies in building level (2)

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

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

3.1.3 Case study

Monahan (2010), reviewed paper no. 7, evaluated energy use, consequential emissions of CO_2, and annual running costs for a case study comprising 14 newly constructed low energy affordable homes located in UK. The carbon embodied in construction and emitted over a 20 years occupation period for 4 different energy typologies which were ground sourced heat pumps; active solar; passive solar and mechanical ventilation; conventional high efficiency gas boiler. The data of energy parameters were gathered from UK's national regulation standards and UK governments SAP(Standard Assessment Procedure) methodology. Energy data was presented in unit of kWh primary energy. Energy costs were based on published average regional pound per kWh prices. System boundary was covered every stage from production to occupation, so that the author considered manufacturing, transportation, installation and maintenance as the embodied GHG emissions factors. The embodied GHGs data for the heating systems and renewable technologies was derived from published literature. Quantities of materials used and sources were gathered from field survey, provided by the installation engineers. Distances from manufacturing to site were calculated from Google Maps. SimaPRO software was used in the analysis. The results shows that ground source heat pumps have the highest annual primary energy demand, GHGs emissions and annual running costs over the 20 year period, while the homes with active solar technologies provided most benefit across all three evaluation criteria.

Ooteghem (2012), reviewed paper no. 16, investigated the breakdown of primary energy use and GWP in a single-storey retail building located in Canada with a 50 year lifespan. 5 different types of buildings were examined to investigate the impact associated with the choice of building materials. The 5 case study buildings were: steel type; timber type; SBS type; steel-PREDOM; timber-PREDOM. These building characteristics were chosen based on a combinationof ASHRAE Standard. System boundary was production to operation stage as previous case study. The ATHENA for Building is used to calculate the embodied energy and embodied GHGs because it is the only software tool currently available in North America. ATHENA, however, is unable to calculate the operating energy consumption and operating GWP of a building directly. Therefore, the author used eQUEST to calculated secondary energy for site energy or operating energy. Once the annual electricity and natural gas use of a building is determined from eQUEST, it can be entered into the ATHENA converter to calculate the resulting total primary energy consumption and total GWP. By converting the secondary energy from eQUEST into primary energy and GWP, the results can be added directly to the embodied energy and embodied GWP results from the ATHENA for Buildings in order to calculate the total energy and total GWP.In the case study, over a 50 year lifespan, the operating energy and operating GWP of the five buildings only differs by3% and 4% respectively. The total embodied energy and embodied GWP differs by as much as 44% and 35% respectively. However, operating effects in these buildings account for around 90% of the total effects and far outweigh any differences in embodied effects between the buildings. Therefore, the total energy and total GWP of these buildings only differs at most by 6% and 7% respectively over a 50 year lifespan.

3.2 Building component level

21 papers have been reviewed in relation to embodied energy/GHGs analysis in building component level. The research subjects in the building component level are various: structure (25%), various building elements (25%); building envelopes (13%); building equipment (13%); wall system (12%); openings (6%); roof system (6%).

Every paper has a tendency to include only environmental factors in embodied energy/GHGs analysis, while only one paper considered economic and social factors in comparison of wood and steel window frame (Abeysundra, 2007). On the whole, the most literature analyzed the embodied energy as environmental factors. The embodied GHGs considered as secondary parameter to compare the environmental impacts from different materials by components. Assessment periods are various from 0 year to 60 years. More than half of researchers did not set the assessment period to analyze embodied impacts from building component. Only a few papers showed the results during 40~60 years lifespan.

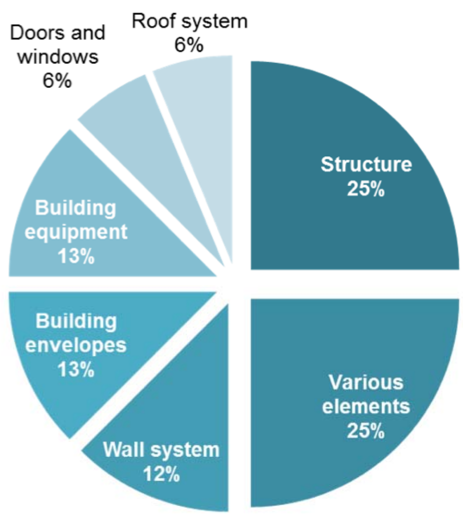


Figure 13. Research subjects in building component level

3.2.1 Methodology

The reviewed papers used process based LCA, I-O LCA, Hybrid LCA, LCEA and Monte Carlo method. The most dominant methodologies are process based LCA and I-O based LCA in the building component level. Unlikely to the embodied energy and GHGs evaluations in building level, I-O based LCA was applied to cases with 0 year lifespan. For example, Gogginset *al.* (2010) used hybrid I-O method to estimate the embodied energy of concrete material in order to minimize the limitations and errors of process analysis and I-O analysis. The result of review on methodology in building component level, however, does not support that there is just one certain superior methodology than the other, depending on system boundary and lifespan setting.

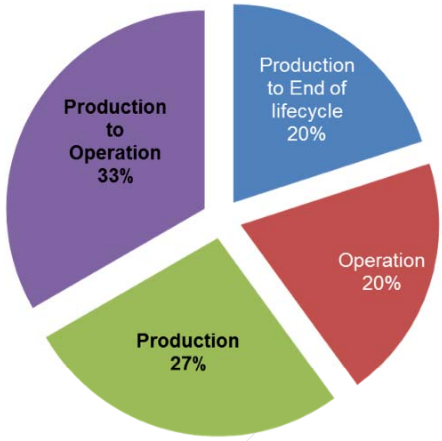


Figure 14. System boundary setting in building component level

The most dominant system boundary setting in building component level is production to operation (33%) and production stage (27%). The reference flow was measured in weight, volume and area unit. The results of embodied energy were expressed in MJ unit, while that of embodied GHGs was commonly measured in GWP, exceptionally one case presented the results in CO_2 and SO_2More specific information related in system boundary and measurement can be found in the table 3 and 4.

3.2.2 Calculation and Database

Almost half of the studies utilized materials and energy data together (47%) to calculate embodied energy/GHG in building component's lifespan, as shown in the Figure 15.The another half of the studies utilized energy data (16%), certification or design guidelines (16%), building material data (10%) and other sources of calculation basis (11%). The other sources of calculation basis were social factors such as durability, sustainability or aesthetics.

The most researchers have obtained data to calculate from field survey and monitoring (37%) and literature (26%). The next preferable data sources are simulation (11%), National statistics database (10%), Ecoinvent (5%) and others (11%). SimaPRO, Easy-fit or Mat-lab software were used as LCA calculation tools. In comparison with energy data source in building level, the case study used energy simulation tools were found relatively less to analyze embodied energy/GHGs of building components.

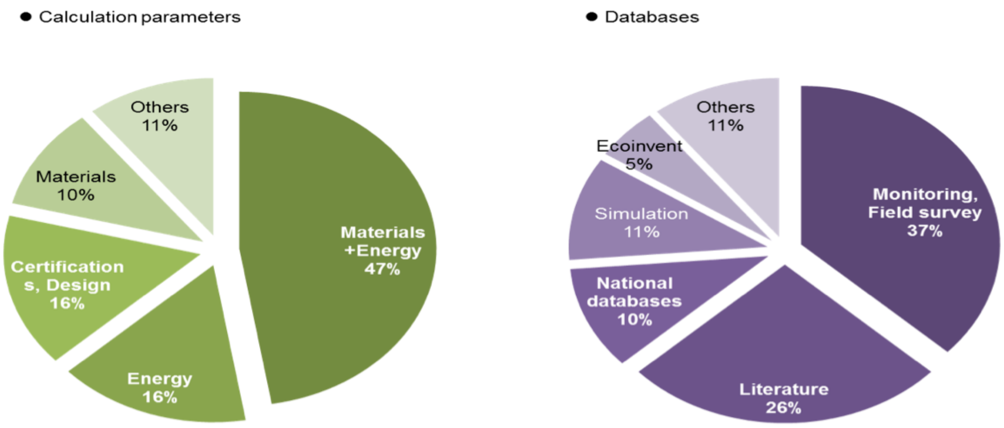


Figure 15. Calculation parameters and the source of LCI DB in building component level

Table 3. Summary of reviewed case studies in building component level (1)

No.	Author (year)	Objectives	Building type	Methodology	Period (year)	Environmental factor				unit	
						EE	OE	EG	OG	EE	EG
1	Cole (1999)	Comparison wood, steel, concrete structure	Building construction	Process based LCA	0	√		√		MJ	GWP
2	Chen (2000)	Analysis	Residential	I-O LCA	40	√				MJ	
3	Emmanuel (2004)	Comparison with different wall system	Wall system	Process based LCA LCC	0	√		√		index	index
4	Crawford (2006)	Analysis BIPV payback	BIPV	Hybrid LCA	1	√	√			GJ	
5	Abeysundra (2007)	Comparison wood, steel window frame	School	Process based LCA	50	√		√		MJ	GWP
6	Dimoudi (2008)	Comparison EE structure vs. envelope	Office	Process based LCA	50	√	√	√	√	MJ	CO2, SO2
7	Utama (2009)	Comparison with different wall system	Residential	LCEA	40	√	√			MJ	
8	Chel (2009)	Comparison passive design vs. none	Residential	Process based LCA	0	√				MJ	
9	Goggins (2010)	Analysis RC structure	Structures	Hybrid LCA	0	√				GJ	
10	Reddy (2010)	Analysis rammed earth walls	Residential	Invented LCA	0	√				MJ	
11	Li (2011)	Comparison wood, steel, concrete structure(oversea products)	Structures	I-O LCA	0	√		√		MJ	GWP
12	Broun (2011)	Comparison with different wall system	Wall system	Process based LCA	0	√		√		MJ	GWP
13	Crawford (2011)	Comparison (roof, wall, floor)	Residential	I-O LCA, Hybrid LCA	50	√	√			GJ	
14	Yu (2011)	Comparison	Residential	Process based LCA	0	√		√		MJ	GWP
15	Chau (2012)	Analysis Carbon footprint by parts	Office	Monte Carlo method	60	√		√		MJ	GWP
16	Huang (2012)	Analysis External shading System	School	Process based LCA	1		√		√	MJ	GWP

Table 4. Summary of reviewed case studies in building component level (2)

No.	Author (year)	System boundary					Reference flow	LCI DB	Tools S/W	Data collection sources		
		P	T	C	O	EOL				field survey	monitoring	Energy simulation
1	Cole (1999)			√				Literature		√		
2	Chen (2000)	√	√	√		√	m^2	Literature		√		
3	Emmanuel (2004)	√	√	√			m^2	Literature		√		
4	Crawford (2006)	√			√		m^2	National LCI DB		√		LCEA
5	Abeysundra (2007)	√					kg	National LCI DB	SimaPRO	√	√	
6	Dimoudi (2008)	√					m^2	Literature		√		
7	Utama (2009)	√	√	√	√		m^2	Indonesian energy mix Literature		√		ECOTECT
8	Chel (2009)	√			√		building			√	√	Energy simulation
9	Goggins (2010)	√	√				kg	National LCI DB		√		
10	Reddy (2010)	√	√	√			m^3	Literature		√		
11	Li (2011)	√					m^2	National LCI DB		√		
12	Broun (2011)	√	√	√	√	√	m^2	Ecoinvent	SimaPRO	√	√	
13	Crawford (2011)	√			√		m^2				√	TRNSYS
14	Yu (2011)	√				√	kg	Literature		√		
15	Chau (2012)	√	√	√	√	√		Literature	Easy-fit, Mat-lab	√		
16	Huang (2012)	√			√	√	m^2			√	√	√

3.2.3 Case study

Utama*et al.* (2009), reviewed paper no. 7, evaluates the effect of building envelopes on the life cycle energy consumption of high rise residential buildings in Indonesia. The study focused particularly on the life cycle energy analysis (LCEA) of building envelope materials associated with air-conditioning. The analysis included the construction of the building envelope and quarrying as well as transportation of materials. Process based analysis used to assess the energy consumed during raw material extraction, material production up to construction, including energy consumption during transportation of intermediate and final materials. ECOTECT was used only to calculate the load associated with the building envelope. The results of embodied energy as well as energy consumed during construction and operation were calculated and normalized to MJ/m^2 floor area for a life time period of 40 years. The results show that the initial embodied energy of Indonesian typical double wall and single wall envelopes for high residential buildings is 79.5 GJ and 76.3 GJ. Over an assumed life span of40 years, double walls have better energy performance than single walls, 283 GJ versus 480 GJ,respectively.

Broun *et al.* (2011) compared the potential environmental impacts and embodied energy based on process based LCA for 3 different alternative partition wall systems with a lifespan of 50 years in UK. The system boundary included the entire life cycle of the partition wall systems, including manufacturing of building materials, construction, operation, maintenance and demolition. Transportation for each life cycle phase is also included. All emissions, energy consumption and materials are based on area unit, e.g. MJ/m^2, kg/m^2. LCI data was obtained from Ecoinvent in SimaPRO software. The main resource for material embodied energy and GHGs in the UK is the Inventory of Carbon and Energy (ICE) Beta 2, developed by the University of Bath. The results indicated that the timber-stud wall has the least environmental impact of the three partition wall systems considered in a UK context, while clay brick partition walls are the greatest environmental impact, but the best potential for reuse.

3.3 Building Material Level

17 papers have been reviewed in relation to embodied energy/GHGs analysis in building material level. The reviewed papers compared the environmental impacts from diverse building materials. The first interesting analysis of embodied energy from building materials was published in 1998 by Harris. With process based LCA method, he calculated 18 major building materials, which are brick, timber (both domestic and imported), clay tiles, concrete, lightweight blocks, crushed granite, aggregate, cement, copper, aluminium, glass, cellulose insulation, mineral wool, synthetic finishes and plastics. Since then, following researchers also tried to compare different materials with similar function, e.g. recycled materials vs. virgin materials or wood vs. other structural material.

Environmental impacts were compared in various points of views, such as primary energy/GHGs or carbon footprint. In the analysis in building material level, embodied GHG factors are relatively more important than embodied energy factor in contrast with that in building component level.

3.3.1 Methodology

Only process based LCA and I-O LCA methodologies were found in the embodied energy/GHGs evaluation in building material level, although the process based LCA was more applied than I-O LCA. About 46% of researchers analyzed embodied energy/GHGs in production to operation boundary. There was no building operational stage assessment in building material level.

The reference flow was measured in weight, volume and area unit. The results of embodied energy were expressed in mostly MJ unit, while that of embodied GHGs was commonly measured in GWP. About 70% of researchers analyzed embodied energy/GHGs in cradle-to-gate boundary including production during 0 year of assessment period. The rest of researchers set 50 or 100 years for assessment. More specific information related in system boundary and measurement can be found in the table 5 and 6.

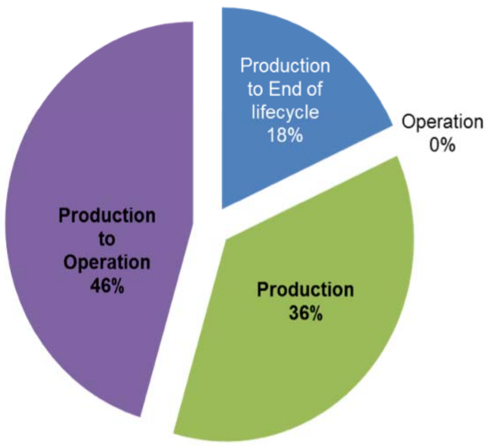


Figure 16. System boundary setting in building material level

3.3.2 Calculation and Database

Calculation parameters in building material level were material and energy together (46%), certification (13%), materials only (7%) and energy only (7%). The certification standards for the parameters were domestic product quality standards. The other calculation parameters (27%) were economic viability, social acceptability, land use and so on.

The most researchers have obtained data to calculate from field survey and monitoring (46%) and national database (27%). Before 2007, the researchers tended to gather calculation data from both field survey and monitoring but recent studies have conducted only with field survey. Just a few cases were found using energy simulation tools such as Quick II or TRNSYS to calculate operational energy/GHGs SimaPRO was the only LCA software used in building material assessment. This implies that the software specialized to calculate energy and GHGs of any types of building materials.

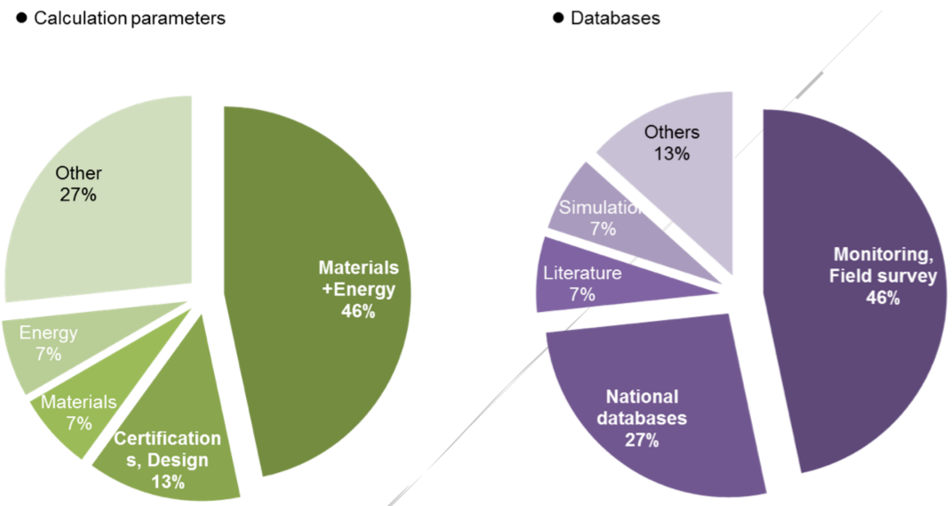


Figure 17. Calculation parameters and the source of LCI DB in building material level

Table 5. Summary of reviewed case studies in building material level (1)

No.	Author (year)	Objectives	Building type	Methodology	Period (year)	Environmental factor				unit	
						EE	OE	EG	OG	EE	EG
1	Harris (1999)	Comparison	Residential	Process based LCA	0	√				kWh/m³	
2	Buchanan (1999)	Comparison: wood vs. other structural materials	Hotel, Office, Industry, Residential	Process based LCA	0	√		√		MJ	GWP
3	Reddy (2003)	Comparison: various masonry materials	materials	Process based LCA	0	√	√			MJ	
4	Gustavsson (2006)	Comparison	Residential	Process based LCA	0	√				GJ	
5	Huberman (2007)	Comparison: building materials	Residential	Process based LCA LCEA	50	√	√	√	√	GJ	GWP
6	Upton (2008)	Comparison: Wood structure vs. RC, Steel	Residential	I-O LCA	100	√		√		MJ	GWP

No.	Author (year)	Objectives	Building type	Methodology	Period (year)	Environmental factor				unit	
						EE	OE	EG	OG	EE	EG
7	Abeysundara (2009)	Comparison	School	Process based LCA	50	√		√		MJ	GWP
8	Yan (2010)	recycled materials vs. virgin materials	office, residential	Process based LCA I-O LCA	0			√			GWP
9	Bribián (2011)	Comparison	materials	Process based LCA CED method	0	√		√		MJ-eq	GWP
10	Crishna (2011)	Carbon footprint of material, UK	dimension stone	Process based LCA	0			√		MJ	GWP
11	May (2012)	Comparison	wood plantation	Process based LCA	0	√				GJ	
12	Aye (2012)	Comparison: steel modular vs RC	Residential	I-O LCA, Hybrid LCA	50	√	√	√	√	GJ	GWP

Table 6. Summary of reviewed case studies in building material level (2)

No.	Author (year)	System boundary					Reference flow	LCI DB	Tools S/W	Data collection sources		
		P	T	C	O	EOL				field survey	monitoring	Energy simulation
1	Harris (1999)	√	√	√	√	√	various			√	√	
2	Buchanan (1999)	√					-	Literature		√	√	
3	Reddy (2003)	√	√	√			m^3	Literature		√	√	
4	Gustavsson (2006)	√					-	Literature		√	√	
5	Huberman (2007)	√	√	√	√	√	m^2	Literature		√	√	Quick II
6	Upton (2008)	√	√	√			-	National LCI DB				
7	Abeysundara (2009)	√					various	National LCI DB BUWAL 250	SimaPRO	√		
8	Yan (2010)	√	√	√			kg	Literature		√		
9	Bribián (2011)	√	√	√		√	kg	Ecoinvent	SimaPRO	European average statistics		CED method
10	Crishna (2011)	√	√				kg	National LCI DB Defra/DECC (2009), IFEU (2008)		√		
11	May (2012)	√					m^3	National LCI DB	SimaPRO	√		
12	Aye (2012)	√			√		t, m^3	National LCI DB Literature		√		TRNSYS

3.3.3 *Case study*

Huberman*et al.* (2007), reviewed paper no. 5 analyzed both embodied and operational energy consumption in a climatic adaptive building in Israel, comparing its actual material composition with a number of alternatives. System boundary was divided into 3 stages: pre-use phase (embodied energy), use phase (operational energy) and post-use phase (demolition or possible recycling and reuse). The total energy budget of a building was assessed by applying the LCEA methodology. Energy flows in the pre-use phase were quantified so as to account for all direct energy inputs, whereas only a part of the indirect energy was included. While ranges of various raw material EE values were obtained from published studies, the embodied energy of major components was calculated by combining the average of available data for raw materials with actual manufacturing processes. In order to quantify the operational energy requirements of the building system for heating and cooling, Quick II software was employed. The analysis did not include upstream indirect EE, recurring EE or post-use energy, and did not address actual economic costs or aesthetic and social image factors. The analysis results showed that the embodied energy of the building accounts for 60% of the overall life-cycle energy consumption which could be reduced significantly by using alternative infill materials for wall. The cumulative energy saved over a 50-year life cycle by this material substitution is on the order of 20%. While the studied wall systems (mass, insulation and finish materials) represent a significant portion of the initial embodied energy of the building, the concrete structure(columns, beams, floor and ceiling slabs) on average constitutes about 50% of the building's pre-use phase energy.

Bribián*et al.* (2011),reviewed paper no. 9, compared the most commonly used building materials with some eco-materials using three different impact categories which were primary energy demand (in MJ-eq) according to the CED method, GWP (in kg CO_2-eq) according to the IPPC 2007andwater demand (in liters).The kg unit was selected as a functional unit and the system boundary included material manufacture, transport from production to building site, construction and demolition of the building, and the final disposal of the product. Calculation data source was Ecoinvent inventories for all analyzed stages. The majority of analyzed building materials in his study was observed to have more environmental impacts between 20~30% greater than that from other previous case study. The study analyzed that was because the hypotheses were more detailed than the other, e.g. data quality requirements, useful life, energy mix, end-of-life scenarios, etc.

4 Findings & Discussions

4.1 Terms and definitions

According to studies[2], life cycle energy and GHGs from a building are divided into two categories; building material's embodied energy/GHGs and building's operational energy/GHGs.(figure 18) Researchers have used the term 'embodied energy' as the sum of all the energy sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal. The term 'operational energy', however, is the opposite concept of embodied energy. Operational energy is the energy used in buildings during their operational phase, as for: heating, cooling, ventilation, hot water, lighting and other electrical appliances. It might be expressed either in terms of end-use or primary energy. The term 'embodied GHGs' has been used as the sum of all the greenhouse gases released from material extraction, transport, material manufacturing, building construction, disposal and related activities. Most researchers give more considerable thought to the embodied energy than embodied GHGs so the results of embodied environmental impacts from building's lifecycle are mostly expressed in terms of embodied energy measurement.

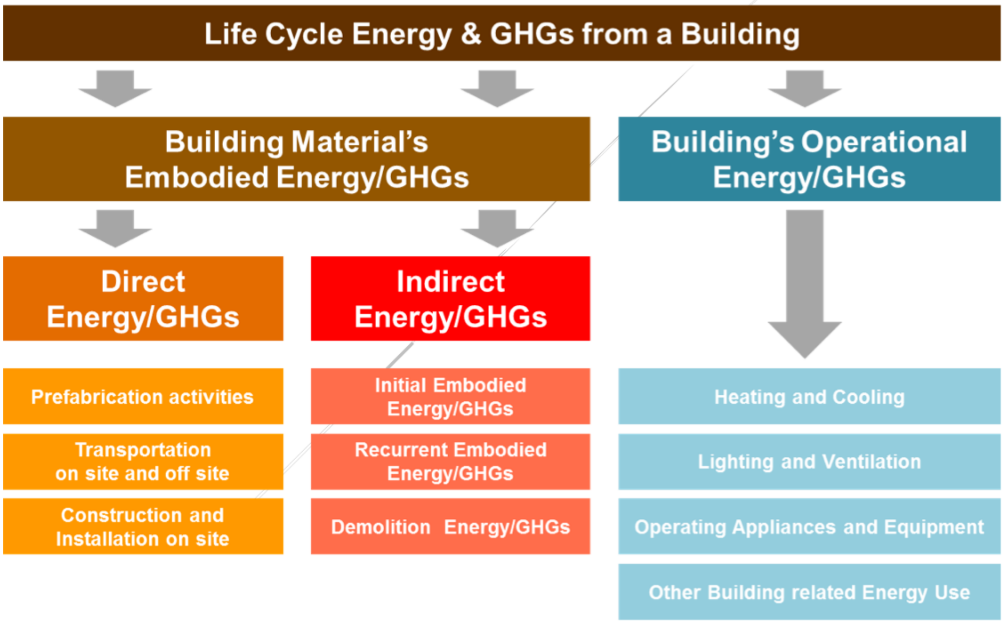


Figure 18. Embodied Energy/GHG and Operational Energy/GHG in building's life cycle

The embodied energy/GHGs is split into direct energy/GHGs and indirect energy/GHGs. Direct embodied energy/GHGs are consumed or emitted in various on-site and off-site operations like construction, prefabrication, and transportation: (1) consumed energy or emitted GHGs in the production of basic building materials, (2) necessary energy or emitted GHGs in the transportation of the building materials, and (3) required energy emitted GHGs for assembling the various materials to form the building. Indirect embodied energy/GHGs are mostly used to explain the environmental

2 Manish Kumar Dixit el al.(2010),Z.M. Chen(2010), I. Sartori , A.G. Hestnes(2007), Reddy(2003)

impacts during the manufacturing of building materials, in the main process, upstream processes and downstream processes and during renovation, refurbishment, and demolition. More specific terms and definitions related in embodied energy assessment in building's life cycle are described as follows:

1) Embodied energy: The sum of all the energy needed It may or may not include the feedstock energy. Generally expressed in term of primary energy.

2) End-use energy: Energy measured at the final use level

3) Feedstock energy*:* Heat of combustion of raw material inputs, such as wood or plastics, to a system. Generally expressed as gross calorific value.

4) Primary energy : Energy measured at the natural resource level. It is the energy used to produce the end-use energy, including extraction, transformation and distribution losses.

5) Direct energy:

- Construction and assembly on-site: Energy inputs during the assembly of building materials and components on-site.
- Prefabrication off-site: Building components that are prefabricated off-site that consume energy in the process
- Transportation: Transportation involved in construction and assembly on-site and prefabrication off-site.

6) Indirect energy:

- Initial embodied energy: Energy used during production of materials and components of a building, including raw material procurement, building material manufacturing and final product delivery to construction-site.
- Recurrent embodied energy: Energy used in various processes for maintenance and refurbishment of buildings (building materials and building components) during their useful life.
- Demolition energy: Energy necessary for deconstruction of building and disposing of building materials.
- Operating energy: Energy required in the building for operating various electrical and mechanical services.

4.2 LCA Methodologies

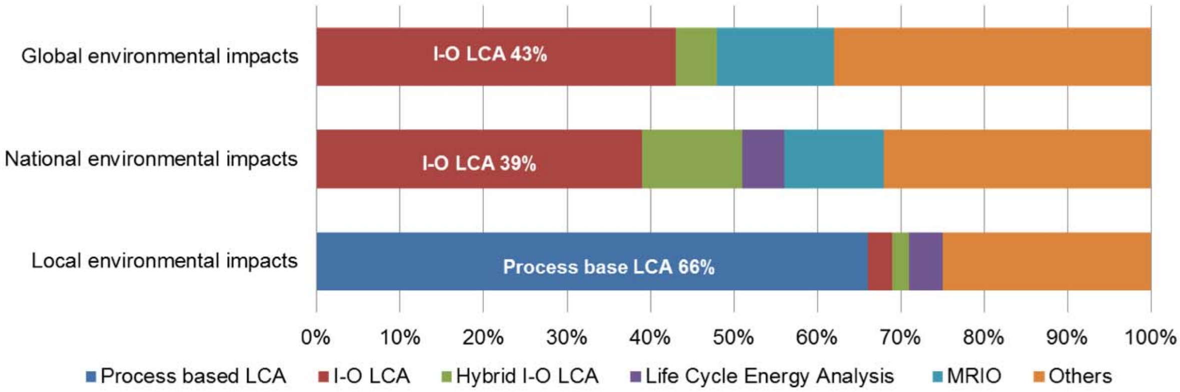


Figure 19. Common LCA methodologies in different level of environmental impacts

The most frequently founded LCA methodologies from the literature review are Process based LCA, I-O LCA, I-O based hybrid LCA, MRIO model, and LCEA. Process base LCA is more applied in order to analyze embodied environmental impacts from very specific subjects such as building, building components or building materials, but never used for national nor global level of environmental impacts. (Figure 19) Rather I-O LCA is more applied to analyze national or global level of environmental impacts. This means there is no one absolute methodology in embodied energy/GHGs assessment in building construction field. Because each methodology has its own advantage and limitation, researchers have chosen different methodologies depend on their subjects and purpose. The characteristics of each methodology are described as follows;

4.2.1 Process based LCA

Process based LCA refers to Bottom-up process analysis that begins at the bottom of the supply chain and pieces together the individual unit processes that make up a product's system. This analysis required data that is collected for each of these processes by measurement and modelling of each process at either local, regional or national levels, although generally the process model will represent a single process or group of processes analogous to a factory or operation.

One characteristic of Process based LCA is its focus on major materials and energy flows and the exclusion of minor and service-oriented inputs. Small material flows may be excluded, as suggested in the ISO standards, based on their mass energy or environmental significance.

4.2.2 I-O based LCA[3]

I-O (Input-Output) based LCA addresses some of the drawbacks of process-based LCA model and greatly expands the system scope compared to the process-based LCA to include the entire economy

[3] Yuan Chang (2010) The embodied energy and environmental emissions of construction projects in China, Energy Policy (38)

of a country or region. It assesses the energy consumption and environmental impacts of goods and services from a nationwide perspective by taking advantage of a country's economic input-output matrix. Then this analysis is refer to a top-down economic technique, which uses monetary transactions between economic sectors rather than physical flows to represent the interrelationships between processes leading to the production of goods and services.

The limitation of I-O based LCA is coarse categorization of economic sectors. For this limitation, all part of the world is represented I-O table that include various sector, but it still represents a problem of gross aggregation.

4.2.3 Hybrid LCA[4]

Because above two methods have advantages and disadvantages for LCA (below table), Hybrid LCA that combines the strengths of both methods has been proposed by researchers. The goal of a hybrid LCA is to combine the advantages of both approaches. There are several types of hybrid models including tiered, I-O based hybrid, integrated, and augmented process-based. These are four examples of hybrid LCA models

4.2.4 Life Cycle Energy Analysis[5]

Life cycle energy analysis (LCEA) is an approach that accounts for all energy consumption to a products or service in its life cycle. The system boundaries of this analysis include the energy use of the following phases (before manufacture, manufacture, use, demolition). This is used for energy use products like as buildings or home appliances. Especially, in the building industry, the materials used in manufacture, operation, and demolition are varied and the range of environmental criteria that are relevant to products is potentially enormous. Then LCEA is effectively used for building worth and sustainability evaluation.

4.2.5 Multi regional input-output model

I-O based LCA does not allow for a distinction between domestic and foreign production technology. However, imports to one country come from a number of different countries and world regions with different production structures and therefore emission and resource intensities. For this reason, Multi-Region Input-Output (MRIO) model was employed. MRIO models endogenously combine domestic technical coefficient matrices with import matrices from multiple countries or regions into one large coefficient matrix, thus capturing trade supply chains between all trading partners as well as feedback effects.

A number of multi-region input-output models with world coverage and results for consumption based accounting and environmental impacts embedded in trade have been presented over the several years. MRIO has being researched all part of the world by national level (Italy, Japan, Netherlands, Scotland, United Kingdom, United States, etc.) and individual level.

[4] Melissa Bilec (2006) Example of a Hybrid Life-Cycle assessment of Construction Processes, J. Infrastructure. System. (12)
[5] T. Ramesh, (2010) Life cycle energy analysis of buildings : An overview, Energy and Buildings 42(10)

4.3 LCI database and tools

A life-cycle inventory (LCI) consists of data collection and calculations to quantify the inputs and outputs of a product life-cycle. This inventory is the heart of the LCA method. LCI analysis involves creating an inventory of flows from cradle to grave for a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. Therefor LCI database is the important key to determine the assessment quality and to minimize the calculation errors.

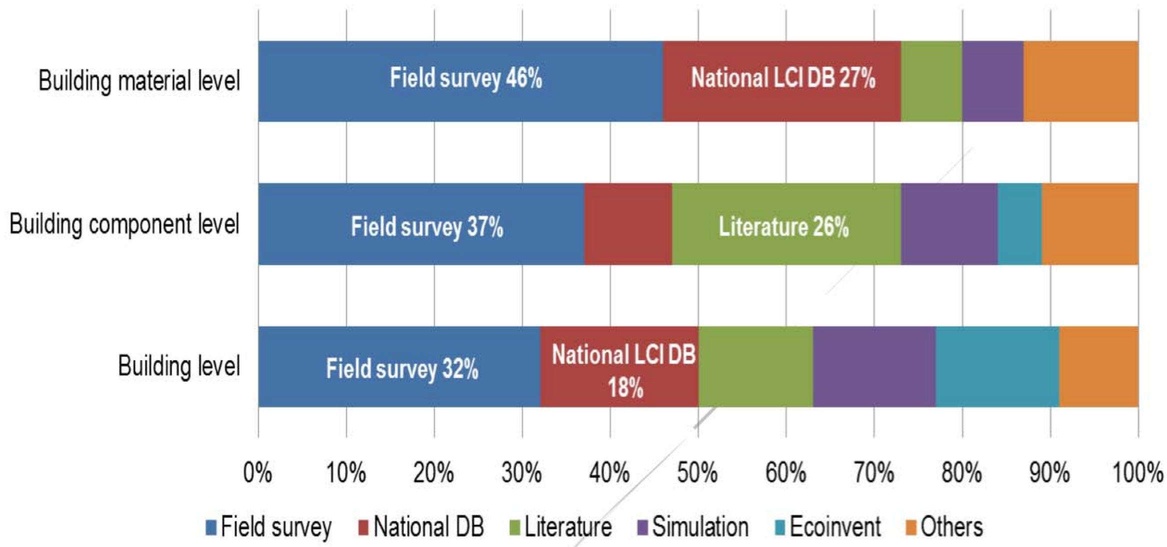


Figure 20. Common LCI DB source in different level of building parts

Field survey is the most common LCI database source for embodied energy and GHGs calculation in every level of building parts during 1990s to 2013.(Figure 20) The next preferable LCI data sources are national LCI DB guidelines and professional software such as ecoinvent. It might be dangerous, however, to refer to results of field survey for calculation factors because published thesis or articles hardly show clear basis of assessment as much as national LCI DB which keeps certain level of data quality. National LCI database network is developed and distributed under government ministry during at least 10 years or more. The countries which operate national LCI database network are described at table 6. GHG guidelines developed by authoritative organization are also reliable to get conversion factors. For example, Defra/DECC published by UK governments is designed to help businesses measure and report their environmental impacts, including greenhouse gas emissions. It has a web based tool containing emission conversion factors for greenhouse gas reporting. Another well-known GHG guideline is Greenhouse Gas Protocol published by World Resources Institute (WRI) and World Business Council on Sustainable Development (WBCSD). These guidelines have been continuously updated to meet the rapid change of companies and societies.

Table 7. National LCI DB list[6]

Country	DB title List	Boundary	Expense
EU	European Platform on Life Cycle Assessment	Europe	Free
Sweden	SPINE@CPM	Worldwide	Charged
Denmark	EDIP	Denmark	Charged
	LCA food	Denmark	Charged
Netherlands	IVAM LCA Data	Netherlands	Charged
	Dutch Input Output	Netherlands	Charged
	Franklin US LCI	USA	Charged
Switzerland	ecoinvent	Worldwide	Charged
	BUWAL 250	Switzerland	Charged
	LCAinfo	-	Charged
	Swiss Agricultural Life Cycle Assessment Database(SALCA)	Switzerland	Charged
Germany	German Network on Life Cycle Inventory Data	Germany	Developing
Thailand	Thailand LCI Database Project	Thailand	Charged
Taiwan	ITRI Database	Taiwan	
Japan	Japan National LCA Project	Japan	Charged
Australia	Austrlian Life Cycle Inventory Data Project	Australia	Free
Canada	Canadian Raw Materials Database	Canada	Free
USA	US LCI Database Project	USA	Free
Mexico	http://www.lcamexico.com	-	-

For adoptable application of LCI DB, a lot of LCA software has been developed by various research organization and company. A various sector make use of this software for LCA analysis and environmental verification. In Korea, for example, various programs have been developed for building sector like as TOTAL, COOL, CLAS, APESS, and some software can linked with foreign software also. And especially, several software like as BEES, ATHENA, Gabi, Simapro are able to construction sector. That software detail information is below.

4.3.1 BEES [7]

The BEES (Building for Environmental and Economic Sustainability) software brings to fingertips a powerful technique for selecting cost-effective, environmentally-preferable building products. Developed by the NIST (National Institute of Standards and Technology) Engineering Laboratory the tool is based on consensus standards and designed to be practical, flexible, and transparent. BEES Online, aimed at designers, builders, and product manufacturers, includes actual environmental and economic performance data for 230 building products.

[6] http://www.edp.or.kr/en/lci/lci_intro.asp, accessed 15 March, 2014
[7] http://www.nist.gov/el/economics/BEESSoftware.cfm, accessed 09 April, 2014

4.3.2 *ATHENA* [8]

Athena Institute software allows construction industry professionals to compare alternate design scenarios and incorporate environmental considerations beginning at the conceptual stage of a project – when most critical decisions are made. All Athena software tools are available for free.

4.3.3 *Gabi* [9]

Created by PE INTERNATIONAL GaBi Databases are the largest internally consistent LCA databases on the market today and contain over 7,000 ready-to-use Life Cycle Inventory profiles. Over 20 years of life cycle expertise by PE INTERNATIONAL is captured in GaBi Databases, which always feature the most accurate Life Cycle Inventory profiles based on primary industry data.

4.3.4 *Simapro*[10]

SimaPro is the most widely used LCA software. It offers standardization as well as the ultimate flexibility. And users build complex models in a systematic and transparent way using SimaPro's unique features such as parameters and Monte Carlo analysis. SimaPro comes fully integrated with the well-knownecoinvent databaseand is used for a variety of applications.

Table 8.List of LCI software

Name	Website	Availability	Language	Geographic Coverage
BEES	http://www.nist.gov/el/economics/BEESSoftware.cfm	Free with contact	English	USA
Boustead Model	http://www.boustedconsulting.co.uk/products.htm	License fee	English	Global
CMLCA	http://www.cmlca.eu/	License fee	English	Europe
ECO-it	http://www.pre-sustainability.com/eco-it	License	English	Global
eiolca.net	http://www.eiolca.net	Free	English	USA
Environmental Impact Estimator	http://www.athenasmi.ca/tools/	License fee	English	Canada, USA
Gabi	http://www.gabisoftware.com	License fee	English, German, Japanese	Global
GREET Model	http://greet.es.anl.gov/	Free	English	USA
IDEMAT	http://www.idemat.nl/	Free	Netherland	Netherland
LLamasoft	https://www.llamasoft.com/	Free for Demo	English Chinese	Global
LCAPIX	http://www.kmlmtd.com/	Free for Demo	English	Global
openLCA	http://www.openlca.org/	Free	English	Global
Windchill LCA	http://www.ptc.com	License fee	English	Global
Quantis Suite	http://www.quantis-intl.com/software.php	Partially Free	English	Global

[8]http://www.athenasmi.org/, accessed 26 March, 2014
[9]http://www.gabi-software.com/, accessed 18 April, 2014
[10]http://www.simapro.co.uk/, accessed 30 March, 2014

Name	Website	Availability	Language	Geographic Coverage
Simapro	http://www.pre-sustainability.com/	License fee	English Japanese	Global
SolidWorks	http://www.solidworks.com/	Free	English	Global
SPOLD Data Exchange Software	http://lca-net.com	Free	English	Global
Umberto	http://www.umberto.de	License fee	English German Japanese	Europe
Total	http://www.edp.or.kr/lci/total.asp	Free	Korean	Korea
COOL	http://www.edp.or.kr/	Free	Korean	Korea
PASS	http://www.kncpc.or.kr/green/lca_pass.asp	Free	Korean	Korea
(SUSB-CLAS) - BEGAS	http://subest.hanyang.ac.kr/	Free	Korean	Korea

4.4 Conclusions

In the past, environmental impacts from building operation were the only issue to evaluate the environmental performance of building. More and more awareness of embodied energy/GHGs, however, has been increased among environmental professionals, companies or other stakeholders as measurements to evaluate environmental impacts from building construction activities since 90s. In this chapter, the results of literature review were discussed to find out any relation between subjects and calculation methods, so more concrete foundation is given to this guideline.

As previously discussed, various LCA methodologies have been applied to assess embodied energy/GHGs in building construction field. Researchers have set different range of system boundaries, research period of assessment, and calculation parameters depend on their study purpose. Every methodology has its own advantages and limitations so it is very hard to suggest the one superior and suitable methodology to assess embodied energy/GHGs. For instance, I-O LCA which is the one of representative LCA methodologies has been widely used to understand impacts from building construction, especially in national or global level of environmental impacts. Process-based LCA, on the contrary, another well-known assessment methodology has been applied more than I-O analysis these days in order to understand local level of environmental impacts. In building level and component level, I-O analysis and process based LCA applied together with Hybrid LCA and LCEA, etc., but in material level only process based and I-O LCA applied.

Therefore it is necessary to suggest a clear framework for embodied energy/GHGs assessment on building’s lifecycle using each methodology in order to compare various results by different environmental professionals. That framework gives users to understand uncertainty and imperfection of their evaluation if they follow a certain methodology. Furthermore it helps users to find out how to reduce calculation errors. Proper source of LCI database and related environmental conversion factors should be provided as information because the number of available LCI data is increasing steadily. Also it is strongly suggested to introduce appropriate calculation methods including system boundary, assessment period and calculation parameters to evaluate embodied energy/GHGs from building’s lifecycle.

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