Life Cycle Energy Analysis of Buildings: A Systems Approach

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STATEMENT

I hereby declare that the work presented in this thesis is original to the best of my knowledge, except as acknowledged in the text. This material has not been submitted, either in whole or in part, for another degree at any University except for the award of degree Doctor of Philosophy (*Philosophiae Doctor*) in Civil Engineering to the Indian Institute of Technology Guwahati.

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CERTIFICATE

This is to certify that the thesis entitled ‘**Life Cycle Energy Analysis of Buildings: A Systems Approach**’, submitted by **Mr Devender Singh Dahiya** bearing Registration No. **136104020** in partial fulfilment of the requirements for the award of the degree Doctor of Philosophy in Civil Engineering to the Indian Institute of Technology Guwahati is a record of the candidate’s own work carried out under my supervision. The matter embodied in this thesis is original and has not been submitted for the award of any other degree.

Date: 19 March 2024

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Last but not least, I thank my family members for being the pillars of my strength to remain focused on the mission.

Place: IIT Guwahati
Date: March 2024

Devender S Dahiya
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This thesis is

dedicated to my dear parents with love . . .

ABSTRACT

Improving the sustainability of buildings is a societal obligation. Buildings consume a large amount of energy and resources, right from their inception to discard and disposal. Most of the energy consumed by buildings is produced from fossil fuels, which result in carbon emissions that lead to climate change. Buildings also generate huge quantities of demolition waste, which needs suitable disposal to avoid its environmental impact. In this direction, one of the United Nations Sustainable Development Goals (SDGs), viz., Goal Number 7, is aimed at improving the energy efficiency or energy performance of buildings across the globe. Therefore, the current investigation is mainly in pursuit of the research question, 'What opportunities exist for improvement in the energy performance of buildings during various stages of their life cycle?'.

The findings from a rigorous systematic literature review of 290 publications indicated some prominent gaps in the existing research. For instance, most of the previous studies on energy analysis of the buildings selected a narrow system boundary focusing only on the building portion while excluding all other components such as the mechanical electrical and plumbing (MEP) services, and site development features, resulting in sub-optimised energy efficiency strategies. In addition, the scarcity of land coupled with high cost has led to increase in vertical development. However, majority of the previous studies have focused on low-rise residential buildings neglecting the energy analysis of high-rise residential buildings. Similarly, the current trend of rapid urbanization and increasing awareness on sustainable development make it imperative to focus research on residential buildings as they consume most of the energy in the building sector. Furthermore, redevelopment of current building stock with the aim of enhancing capacity often necessitates the demolition of high-rise residential buildings using controlled explosion; however, a study on this aspect is rarely found in publications. The current study is intended to address these gaps, with the aim of carrying out the life cycle energy analysis of a high-rise residential building project.

The study has adopted the case study research method to fulfil its objectives. The findings of this study are based on the energy analyses of a single high-rise residential building project due to constraints on data availability arising from technical and commercial concerns. The scope of this study has been extended to include all stages and sub-stages of a building project life cycle from the pre-occupation stage to the occupation stage, and

the post-occupation stage. Apart from the residential towers, the scope also includes all components of the residential building project such as the services and the site features.

Primary data has been collected as documentary evidence from sources such as contract documents, and facility management records for pre-occupation and occupation stages respectively. This was followed by semi-structured interviews to gather the primary data relating to the post-occupation stage. In the post-occupation stage, the building project was taken up for prospective demolition at the end of the building project life span of 50 years using a controlled explosion. The analysis of prospective demolition has been carried out using primary data collected from the actual demolition of similar buildings. The data analysis was carried out using a combination of quantitative analysis techniques such as input-output based hybrid analysis during the pre-occupation stage, simple arithmetic during the occupation stage, and input-output analysis during the post-occupation stage.

The energy analysis from the case study building project reveals that, during the pre-occupation stage, the residential towers sub-system consumed the highest share of 56% of initial embodied energy of the building project system, while MEP sub-systems (inclusive of external water supply, external electric supply, STP, firefighting, elevators and HVAC) consumed a sizeable proportion of 26%. Further, in the building portion of the project, steel, concrete, bricks and cement together had a large share of 98% of the total weight and also contributed to 90% of the total initial embodied energy.

During the occupation stage, MEP sub-systems consumed the largest share (47%) of the total recurring embodied energy (REE) due to frequent replacements and higher cost of maintenance. In the case of operating energy, building related[1] sub-systems (residential tower and parking sub-systems) and non-building[2] sub-systems (MEP services, site development, sports, and site beautification sub-systems) consumed 46% and 54% of the total operating energy, respectively. Amongst the MEP services, HVAC contributed to the highest proportion of operating energy (34%) for space heating and cooling requirements.

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[1] building related sub-systems pertain to residential tower and parking sub-systems.

[2] non-building sub-systems include. MEP services, site development, sports, and site beautification sub-systems

Relating to the post-occupation stage, building related sub-systems produced the highest proportion of demolition waste (81%) and demolition energy (74%). Whereas non-building sub-systems generated 18% of total demolition waste and consumed 20% of the total demolition energy. The waste generation rate of the building project is estimated to be 1715 kg/m^2.

The collective share of energy consumption or recovery by the MEP and site features sub-systems varies from 20% to 55% during various stages of the life cycle. Hence, the influence of these non-building sub-systems on the energy performance of building projects can no longer be ignored. These findings highlight the need to include complete system boundaries to enable realistic energy analysis and formulation of pragmatic strategies for reduction in energy and environmental burdens of the building projects. At the same time, the above share of energy consumption of various sub-systems is likely to differ with change of scenario such as differing building projects or differing climates.

This study reinforces the necessity to recognise the importance of using country-specific embodied energy coefficients to improve the accuracy of results and to afford a realistic comparison with similar studies. The study also recommends several strategies for improvement in the energy performance during various stages of the building project life cycle based on the opportunities identified during the energy analysis of the case study project. Some of the key recommendations comprise: use of passive solar architecture and incorporation of low-embodied energy and recycled materials during the pre-occupation stage; use of energy-efficient equipment and appliances in the occupation stage; and leveraging innovative methods such as design for deconstruction and robotic demolition during the post-occupation stage.

Additionally, the findings of this study draw attention to some significant research implications for key stakeholders. For instance, the study dictates the undertaking of policy initiatives such as the creation of a sustainable market for energy-efficient buildings, the establishment of a formal data exchange mechanism on construction projects for stakeholder use, and the provision of environmental product declarations (EPD) by the manufacturing industry. Similarly, some other important implications include: the use of a design for deconstruction approach; the evaluation of design alternatives from a life cycle perspective; and the development of new materials to reduce the usage of concrete and materials with higher recycling potential.

The contribution of this study lies in conducting the life cycle energy analysis of high-rise residential buildings at the building project scale, thus highlighting the relevance of MEP services and site features, which were mostly neglected by past studies while formulating energy efficiency strategies for building projects. Furthermore, the study has attempted to bridge a vital gap in the knowledge repository on the estimation of demolition energy consumption in high-rise residential building projects using controlled explosion. Additionally, the study is expected to be helpful to stakeholders in identifying opportunities for improvement in the energy performance of building projects during various stages of their life cycle.

Finally, the study identifies the limitations of the current investigation and also gives out the scope for further research.

Keywords: High-rise buildings, residential building projects, life cycle energy analysis, building performance, systems approach, system boundaries, embodied energy, operation energy, demolition energy, pre-occupation stage, occupation stage, post-occupation stage, input-output hybrid analysis, input-output analysis, controlled explosion, demolition waste.

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ABBREVIATIONS

Abbreviation	Full Form
DE	Demolition energy
EE	Embodied energy
IEE	Initial embodied energy
I–O	Input-output
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
$LCCO_2A$	Life cycle carbon dioxide analysis
LCE	Life cycle energy
LCEA	Life cycle energy analysis
MEP	Mechanical, electrical and plumbing
OE	Operating energy
REE	Recurring embodied energy

Currency Standards and Exchange Rate

- USD - US Dollar
- Rs - Indian Rupee or INR
- 1 million = 10 Lakh
- 1 Lakh = 0.1 million
- 1 USD = 82.770 INR as on 30 August, 2023 (Reserve Bank of India, 2019)

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The construction industry has wide-ranging social, economic and environmental impacts on society across the globe. Construction activities have some positive outcomes, such as the provision of shelter and facilities to meet various functional requirements, affording direct or indirect employment opportunities through construction related industries, and contributing toward the growth of national economies. For instance, the construction industry accounted for about 13% of global GDP in 2020 (Robinson et al., 2021) and provided more than 220 million jobs in 2018 (International Labour Organization, 2019). On the other hand, building construction is also associated with noise, dust, waste generation and water pollution.

Globally, the building sector consumed more than 30% of total final energy and produced nearly 30% of energy related CO_2 emissions in 2018 (International Energy Agency [IEA], 2019). In the building sector, energy is consumed in the form of both direct energy (Chen et al., 2022) and indirect energy (Skillington et al., 2022). During the pre-occupation stage, direct energy is utilised for the extraction of raw material, transportation of material to the manufacturing site, production of construction material, transportation of material to the construction site, and actual construction on site. On the other hand, indirect energy is expended on all aspects related to planning and design, and management of the project during construction,

Similarly, during the occupation stage, direct energy is consumed for heating of water, space heating and cooling, lighting, cooking, and operation of appliances and services (Ahmadi-Karvigh et al., 2018; Frayssinet et al., 2018). At the same time, indirect energy is consumed for the management of facilities, including the operation of services, housekeeping, and provision of security. In addition, direct and indirect energy is consumed for the repair, maintenance, and replacement of building components (Mourao et al., 2019).

During the end-of-life or demolition phase, direct and indirect energy is required for the deconstruction/demolition of the building structure, transportation of demolition waste to recycling plants or landfill dumps, and during the recycling process (Stephan & Stephan, 2016). In addition, the end-of-life phase also results in producing large amounts of demolition waste. For instance, the Chinese construction industry generated 1134 million tonnes of waste in 2014 in the construction and demolition of buildings (Lu, 2014). In Australia, 43% of construction related waste was consigned to landfill (Tam & Lu, 2016). The increasing demand for landfill space presents a challenge to urban areas and countries with limited land availability, such as small island countries (Kang et al., 2022).

Construction, operation, and demolition of buildings are, thus, associated with the consumption of a large quantum of resources in terms of material, labour, and energy. What concerns more is that about two-thirds of the global building sector energy demand is met by fossil fuels, which have the highest carbon emission content among all other fuels that adversely impact the environment (UN Environment and IEA, 2017). Some of the environmental issues of concern include climate change, eutrophication, resource depletion, acidification, and ozone depletion (International Organization for Standardisation [ISO], 2022).

Considerable scope exists for energy conservation by improving the energy efficiency of buildings and the use of power efficient appliances (Mariano-Hernández et al., 2021). Similarly, the use of clean fuel such as natural gas in place of coal for electricity production, the use of renewable energy, the shift from fossil fuel to LPG for cooking, and the use of electric heat pumps in place of natural gas and oil for space heating can result in reduction of CO_2 emission to a large extent (Pistochini et al., 2022).

Though efforts towards the construction of energy efficient, sustainable buildings are underway, the energy demand of buildings is on the rise due to ever-growing developments in the building sector (GlobalABC, 2019). Therefore, as the building sector is poised for unprecedented growth that would increase the energy and environmental burdens, prima facie, the building sector has considerable potential for energy conservation and scope for further research.

1.2 MOTIVATION AND RESEARCH QUESTION

The rate of growth in world GDP, a fundamental driver of energy demand, is expected to average 3.6% per year over the period 2009 to 2035. China and India alone make up 31% and 15% of the increase in global GDP to 2035, respectively. Population growth will continue to underpin the rising energy demand as the world's population is estimated to increase by 26%, from 6.8 billion in 2009 to 8.6 billion in 2035 (IEA, 2011).

Consequent to the rise in global GDP and population, the overall primary energy demand is expected to grow at an average rate of 1.03% per year and rise by 25% from 14314 million tonnes of oil equivalent (Mtoe) to 17723 Mtoe between 2018 to 2040 in the stated policies scenario (IEA, 2019). Similarly, the global per capita floor space demand in the residential sector is estimated to grow from 26 m^2 to 35 m^2 and that in the non-residential sector from 5.9 m^2 to 9.5 m^2 between 2017 and 2050 (Det Norske Veritas, 2017). Resultantly, building sector annual energy demand is projected to rise from 2971 Mtoe to 3769 Mtoe during 2017 to 2050 (IEA, 2021b) and building sector energy related emission is set to grow from 8.8 Gt CO_2 /year in 2010 to 13 – 17 Gt CO_2 /year in 2050 in base-line and mitigation scenarios (Edenhofer et al., 2014).

In the Indian context, the overall primary energy demand is projected to grow at an average rate of 4.38% per year and more than doubles from about 916 Mtoe to nearly 1841 Mtoe between 2018 and 2040. Also, the total electricity demand is likely to grow at an average rate of 5.1% and increase almost three times from 107 Mtoe to 319 Mtoe over the same period (IEA, 2019). In addition, energy related CO_2 emissions increase at an average rate of over 2% from 2.3 Gt of CO_2 to 3.4 Gt of CO_2 during 2019 to 2040 (IEA, 2021a). Similarly, the building sector electricity demand is estimated to rise at an average rate of about 9.5% from 489 terawatt hour (TWh) to 1512 TWh between 2019 and 2040, and electricity related CO_2 emission will grow at an average rate of 2% from 354 Mt to 508 Mt, despite a cumulative fall of 45% in CO_2 intensity of electricity production during the same period in the stated policy scenario (IEA, 2021a).

Over the last decade, the Indian residential sector has exhibited impressive growth, mainly riding on catalytic factors such as rise in population, improvement in per capita income and fast-paced urbanisation. India's urban population is predicted to rise from 377.1 million in 2011 to over 600 million by 2031. This rapid growth in urbanisation has resulted in a manifold increase in demand for housing, services and public infrastructure. While the residential floor area is projected to increase from 270 Mm^2 to 1858 Mm^2, the commercial built-up area is expected to increase from 1515 Mm^2 to 6500 Mm^2 between

2005 and 2030 (Planning Commission, 2012). This increase in the built-up area would entail a corresponding increase in the energy demand and consumption of the building sector.

The residential sector in India consumes nearly 75% of the total electricity consumed in the building sector (Bureau of Energy Efficiency [BEE], 2018). The sector-wise electricity consumption in India is shown in **Figure 1.1.** The electricity demand from residential and commercial buildings makes up about 29% of the total electricity consumption, with a growth rate of nearly 8 per cent per annum. Most of the above power is consumed to meet the lighting, and heating and cooling requirements of the buildings. Moreover, the energy demand of buildings is expected to maintain upward growth due to continued expansion in IT-enabled services (ITES) and the hospitality sectors (Planning Commission, 2012).

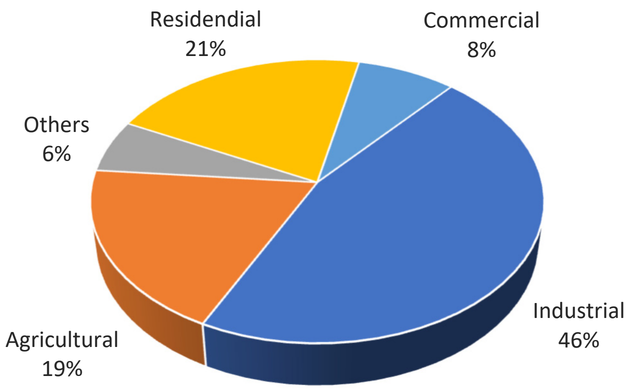

Figure 1.1 Sector-wise electricity consumption in India
Adapted from Planning Commission (2012)

The real cause for concern is that about 80% of the global energy demand is met from various forms of fossil fuels (coal, oil and natural gas). The use of fossil fuel for energy production is characterised by a low conversion efficiency and high emission factor. For instance, fossil fuels' average global conversion efficiency for power production is just 37% due to losses in production, transmission and distribution for final use. Consequently, global energy related greenhouse gas (GHG) emissions currently account for a substantial proportion (nearly 70%) of the total emissions from all sectors (Edenhofer et al., 2014).

Concerned with the unabated rising of GHG emissions and their global warming potential, in September 2015, the United Nations (UN) adopted the new Sustainable Development Goals (SDGs) for the year 2030 (IEA, 2022). One of the targets of the UN's SDGs (Goal No.7) is to double the global rate of improvement in energy efficiency from an average of 1.3%/year over the period 2000-2015 to 2.7%/year during 2015-2030. Towards this end, most countries have set their priorities to improve energy efficiency in the three highest energy consuming sectors, namely, the industrial, building and the transport sector (IEA, 2016).

As the residential sector accounts for a large share of total energy consumption and consequent environmental impacts, energy analysis of residential buildings is increasingly becoming the focus of research attention. Several efforts are underway towards improving the energy efficiency or energy performance of residential buildings. One of the efforts in this direction has been towards the assessment of energy consumption with the key motive of identifying the opportunities for improving the energy efficiency or energy performance of buildings.

Additionally, a systematic literature review undertaken during this study revealed lack of adequate research on high-rise residential buildings, and studies performed at the project scale. Further details of the systematic review are given in Chapter 2: Review of Literature.

Based on these motivations, the general research question of the current study is formulated as follows:

'What opportunities exist for improvement in the energy performance of high-rise residential building projects during their life cycle?'

1.3 RESEARCH AIM AND OBJECTIVES

The aim of this research is to carry out the life cycle energy analysis of a high-rise residential building project. The four research objectives that emanate based on this aim are:

a) To estimate the embodied energy utilised by various components of a high-rise residential building project during the pre-occupation stage.
b) To study the energy demand of various components of a high-rise residential building project during the occupation stage.
c) To investigate the demolition energy consumption of various components of a high-rise residential building project during the post-occupation stage, and
d) To analyse the overall energy requirements of a high-rise residential building project during its entire life cycle.

1.4 RESEARCH SCOPE

This study focuses on the life cycle energy analysis of a high-rise residential building project. The scope of the study includes all components or sub-systems, such as the residential buildings (towers), mechanical, electrical and plumbing (MEP) services and site development features. The study considers energy analysis during all the stages and sub-stages of a building project life cycle, i.e., the pre-occupation or pre-use stage, use/operation or occupation stage, and demolition/end-of-life or post-occupation stage.

1.5 ORGANISATION OF THE THESIS

The thesis is organised into eight chapters, and the focus of each chapter is outlined as follows: -

Chapter 1 introduces the background and motivation of the current study. This chapter also brings into focus the general research question, along with the narrative on the general layout of the thesis. It also enumerates the aim and objectives, apart from the scope of the current study considered.

Chapter 2 presents the literature review findings, giving an overview of the state of research on energy analysis of buildings while identifying the research gaps. This chapter highlights the research questions that guide the formulation of the objectives of this research.

Chapter 3 discusses in detail the research methodology adopted to accomplish the research objectives of this study. It also briefly describes the case study building project and discusses the systems model as identified from a review of project documents.

Chapter 4 brings further clarity on research gaps addressed during the energy analysis in the pre-occupation stage. Thereafter, it presents the research method adopted, results obtained and discussion on energy analysis of case study building project during the pre-occupation stage. It also demonstrates the relevance of geographical representativeness while estimating the embodied energy of the building project.

Chapter 5 deliberates on the research method adopted, results and discussion on energy analysis of case study building project during the occupation or the operation stage. This chapter elaborates on recurring energy incurred for repair, maintenance, and replacement of components/material of each sub-system. In addition, it also encompasses the energy requirement of each sub-system during the operation stage of the building project.

Chapter 6 presents additional research gaps identified and covered during the energy analysis in the post-occupation stage. Thereafter, it focuses on the research method adopted, findings and discussion on energy analysis of case study building project during the post-occupation or the end-of-life stage. It also describes the details of data collection from the actual demolition of a high-rise residential building using controlled explosion.

Chapter 7 sums up the cumulative energy burdens during the complete life cycle of the case study building project. This chapter presents the contribution of various life cycle stages in the life cycle energy footprint of the building project. It further discusses the results of sensitivity analysis on the life cycle energy of the building project.

Chapter 8 summarises the key conclusions from the study, identifies limitations of this study and suggests directions for future research. This chapter also highlights the research contribution, research implications, and strategy recommendations for improving the energy performance of a residential building project during various life cycle stages.


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CHAPTER 2: REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter presents a review of the literature to identify the prospective areas of research not adequately covered by the previous studies in terms of the type of buildings, the system boundaries and the scope of building projects for realistic energy analysis. To fulfil this aim, the literature has been reviewed using a scoping literature review followed by a systematic review approach to afford further clarity on the subject. The scoping literature review helped in identifying *the appropriate type of energy analysis to be carried out for the energy analysis of buildings*. On the other hand, the systematic literature review was helpful in ascertaining the *state of the art on building energy analysis* concerning the identification of prospective areas for further research. In addition, it also afforded clarity on the formulation of research questions, the research problem, and the aim and objectives of the current study.

During the period of review, building energy concepts have evolved from conventional buildings to low-energy buildings, near-zero-energy buildings (nZEB), net-zero-energy buildings, zero-energy buildings (ZEB), and finally, energy-plus buildings. Similarly, the issue of ‘net zero carbon’ by the year 2050 is currently under global focus as mandated by the Paris Agreement of 2015 (Gil & Bernardo, 2020). It is important to note that the term ‘net zero energy’ implies that a building, apart from being energy efficient, is also able to meet all its energy requirements during the operation phase through onsite or offsite production of energy from renewable sources. Whereas, the term ‘net zero carbon’ applies to energy-efficient buildings that generate zero emissions during all stages of their life cycle. The ‘net zero carbon, or ‘carbon neutrality’ is a more holistic concept that involves the circular economy approach in addition to the use of green energy during the complete building life cycle, thus accruing economic, environmental, and societal benefits for increased sustainability.

Researchers, architects, engineers, and manufacturers are constantly working to improve building energy performance. However, lack of motivation for the construction of low energy buildings due to high perceived cost and absence of demand for low energy buildings due to poor stakeholder awareness are some of the barriers being encountered in the proliferation of energy conscious building construction (Giesekam et al., 2016; Guribie et al., 2022).

2.2 SCOPING LITERATURE REVIEW

A large amount of work has been done on building energy analysis to ascertain the energy performance of buildings. Different researchers have focused on different areas of building energy. Some prominent areas of interest include codal provisions, embodied energy analysis, operating energy analysis, whole building rating systems, life cycle assessment and life cycle energy analysis. The subsequent sub-sections will discuss the prominent areas of interest identified from the scoping review.

2.2.1 Building energy codes and energy certification: International

A large amount of work has been done on building energy analysis to ascertain the energy performance of buildings. Different researchers have focused on different areas of building energy. Some prominent areas of interest include Codal provisions, embodied energy analysis, operating energy analysis, whole building rating systems, life cycle assessment and life cycle energy analysis. The subsequent sub-sections will discuss the prominent areas of interest identified from the scoping review.

Building energy codes

Building energy codes and standards (Boza-Kiss et al., 2013) such as ANSI/ASHRAE/IES Standard 90.1-2019, Energy Efficiency Standard for Buildings Except Low-Rise Residential Buildings (US), ANSI/ASHRAE 90.2-2018: Energy-Efficient Design of Low-Rise Residential Buildings (US), ISO standards on LCA, For example, ISO 14040:2006 LCA—Principles and framework, and ISO 14044:2006 LCA—Requirements and guidelines, Energy Performance of Buildings Directive (EPBD) (Europe), Zero Energy Standard (Green Building Council Brazil), Zero Carbon Building Standard (Canada Green Building Council) and Leading Efficiency Programme (LEP) (China) are some examples of global commitments on improvement of building energy performance,

Energy performance assessment

Energy performance is a term to indicate the quality of a building in energy use (Poel et al., 2007). Energy performance indicators (EPI) are quantifiable measures to assess energy performance. The most commonly used EPI for many building types is energy use intensities (EUI), i.e., kWh/m^2. Building energy performance is mainly determined by six factors: (1) climate, (2) building envelope, (3) building services and energy systems, (4) building operation and maintenance, (5) occupants' activities and behaviour and (6) indoor environmental quality provided, as summarised in IEA Annex 53 project (Yoshino et al., 2017). The objectives of building energy performance assessment are energy classification and energy performance diagnosis. Energy classification provides uniform or authorised means to communicate a building's relative energy efficiency and carbon emissions to both the owners and the public to encourage ongoing efficiency and conservation gains (Wang et al., 2012).

Energy classification/certification

Energy classification is an information instrument that provides building owners or the public with information regarding the energy performance of the assessed buildings. Such information is usually expressed in a convenient and understandable form, such as 1 to 100, A to M, or poor to excellent, so it encourages better performance with higher acknowledgement and motivates building owners to improve energy performance. Several cost-effective, mandatory and voluntary regulatory instruments have emerged in practice, including energy benchmarking, energy rating, energy labelling and energy certification (Lucon et al., 2014). Each has its uniqueness in classifying the quality and displaying the level of energy performance, while sometimes they have overlapping meanings and can even be replaced by each other (Pérez-Lombard et al., 2009). Furthermore, carbon pricing (Kaufman et al., 2016), and energy pricing (Thomas et al., 2019) also help reduce energy demand. However, a word for caution on energy policies and legislation is to guard against the rebound effect due to behavioural shifts (Gillingham et al., 2013) and macroeconomic effects (Zhang & Lawell, 2017).

Around 85 countries have mandatory or voluntary building certification policies by 2018 (GlobalABC, 2019). Leadership in Energy and Environmental Design (United States Green Building Council, 2020), (United States), BRE Environmental Assessment Method (BREEAM, 2022) (United Kingdom), Green Star (Green Building Council of Australia, 2022) (Australia), Green Mark Scheme of Building and Construction Authority (BCA, 2021) (Singapore), Deutsche Gesellschaft für Nachhaltiges Bauen Certification (DGNB, 2022) (Germany), and Comprehensive Assessment System for Built Environment

Efficiency by Institute for Building Environment and Energy Conservation (IBEC, 2022) (Japan) are some of the leading green building certification tools.

2.2.2 Building energy codes and energy certification: India

In India, Energy efficiency initiatives have also been undertaken with the formulation of the National Building Code 2016, which helps lay down the guidelines for sustainable development to rationalise the impact of development on its neighbouring areas (Bureau of Indian Standards [BIS], 2016). Similarly, building energy certification is offered by three main agencies, i.e., Green Rating for Integrated Habitat Assessment (GRIHA) Council, Indian Green Building Council (IGBC) and Bureau of Energy Efficiency (BEE). Furthermore, BEE has issued two separate codes for energy conservation of commercial and residential buildings such as the Energy Conservation Building Code (BEE, 2017) for commercial buildings with a connected load of 100 kW or greater or a contract demand of 120 kVA or greater; and Eco-Niwas Samhita 2018 (Part-I) Building Envelope for residential buildings built on a plot area of more than 500 m^2, but this code does not include the electro-mechanical equipment and embodied energy of walling materials and structural systems (BEE, 2018). On the other hand, GRIHA and IGBC provide green building certification on similar lines to other international tools such as LEED (US) and GBCA (Australia). GRIHA and IGBC certification systems are better suited for building certification in India as these two systems have been developed based on Indian codes and standards. Additionally, GRIHA and IGBC systems have been tailored to the five climatic zones: hot and dry, warm and humid, temperate, composite, and cold, as per climate classification in the National Building Code 2016 (BIS, 2016).

The review of these building energy codes and certification policies highlights certain limitations in the current system. One of the critical observations is that most energy codes focus on new buildings while neglecting the existing build stock that would account for most energy needs for space heating in 2040 (IEA, 2016). Secondly, the above methods either tend to be subjective or allot credits for non-energy saving features. Furthermore, these methods need refinement on issues such as system boundaries, methodology for calculation, and data availability and quality (Dixit et al., 2012). Moreover, in some cases, the energy consumption of green certified buildings was found to be even more than conventional buildings and the national average energy consumption (Menassa et al., 2012; Newsham et al., 2009). *Therefore, energy rating using life cycle* *energy analysis by far appears to be a more precise method of measuring building energy performance (for instance., the rating expressed in kWh/m*^{2}*/year).*

2.2.3 Energy analysis during various stages of building life cycle

Past research on building energy has focused on different life cycle stages. A number of authors have argued on the indisputable primacy of the operation stage for causing energy and environmental impact of buildings. The main reasons cited in support of this argument have been that the operation phase is the longest of all other stages, and it also has to cater for the large requirement of energy for the heating and cooling needs of the occupants (Adalberth et al., 2001; Ortiz et al., 2009). Some of the studies found that the operating energy of a building ranged from 70% -90% of the total life cycle energy demand, while the embodied energy consumption could vary from 10%-30% (Adalberth, 1999; Cole & Kernan, 1996).

This argument may be understandable in respect of conventional and old buildings. But with increasing awareness on sustainability and consequent enforcement of minimum energy performance standards (MEPS) in most countries, the trend to construct energy efficient and low energy buildings is on the rise. Thus, the interrelation between operating energy and embodied energy is changing (Chen et al., 2001; Citherlet & Defaux, 2007). Therefore, another group of studies dwelt upon embodied energy related aspects of building energy. It was observed that the use of measures to minimise operational energy, such as an increase in the thickness of insulating material and the use of energy efficient equipment and appliances, resulted in a rise in embodied energy (Rakhshan et al., 2013), and the embodied energy could vary from 30 to 60 % of the building life cycle energy in the new and low energy buildings (Leckner & Zmeureanu, 2011; Villa et al., 2011) On the other hand, some authors have demonstrated the significance of the end-of-life phase of the buildings due to the enormous potential for the reuse/recycling of demolition waste in promoting a circular economy (Nußholz et al., 2019; Thormark, 2006).

Notwithstanding the importance of each individual stage of a building life cycle in promoting sustainability, it is strongly believed that the energy and environmental impact of these stages is “highly interdependent” (Blengini & Di Carlo, 2010), and these stages should not be considered in isolation. For example, the design and construction of buildings using passive solar architecture may result in a reduction of operational energy requirements but, at the same time, could result in higher embodied impacts due to the use of additional building materials and increased transportation during the construction stage, apart from higher transportation needs on disposal of increased demolition waste. Therefore, *life cycle analysis (LCA) or life cycle energy analysis (LCEA) of buildings is increasingly gaining momentum among researchers (for instance, Hong et al. (2016), Evangelista et al. (2018)) for a complete and realistic energy and environment assessment.*

2.3 SYSTEMATIC LITERATURE REVIEW

2.3.1 Research Method

A systematic literature review was undertaken to enable a critical synopsis of the research topic under investigation (Sartor et al., 2014). In the past, systematic reviews have been carried out on various aspects of building energy. For example, Al-Zubaidy (2015) has systematically reviewed Energy Efficiency of Leadership in Energy and Environmental Design (LEED) certified buildings. Another systematic review on the energy performance of double-skin façades in temperate climates was reported by Pomponi et al. (2016). However, it could be observed that a systematic literature review on the life cycle energy analysis of buildings has not been attempted to date.

In this study, the definition of systematic literature review stated by Fink (Fink, 2019) has provided the guiding concept. The conceptual scheme of the current review process, based on Pautasso (2013), is presented in **Figure 2.1**. The first four steps of the review process are discussed in this section, while the next section on Material Evaluation deals with the steps such as Assessing the quality of results and Extracting the required data. Data synthesis has been carried out, and significant observations from this review are discussed below in Section 2.4 of this chapter.

Five databases, viz., Scopus, Science Direct, Ebscohost, Web of Science, and SpringerLink, have been selected for material selection to answer the research question – *What is the state of art on the life cycle energy analysis of buildings?* The material collection process adopted for this study is shown in a flowchart **(Figure 2.2).** A basic search was performed in these databases using the search query, “life cycle AND energy and buildings” OR “life cycle AND energy AND buildings projects” OR “life cycle AND energy AND buildings materials.” An advance search was then carried out using specific inclusion and exclusion criteria based on delimiters such as Categories, Source Type, Source Titles, Document Type, Timespan, and Language.

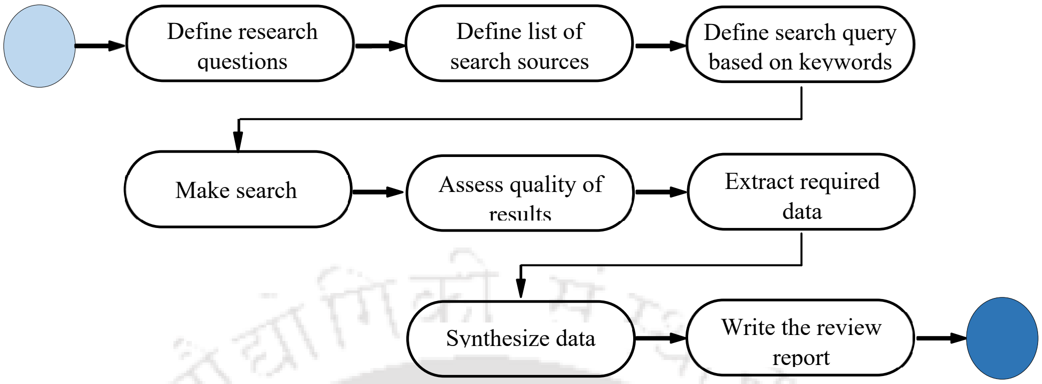


Figure 2.1 Conceptual scheme of the systematic literature review process (Adapted from Pautasso (2013))

Articles not written in English were excluded due to the disproportionate effort involved in their translation. The review was conducted for a period of 25 years, from 1995 to 2019. Articles published before 1995 were not included due to poor and scattered reporting across databases. Books, periodicals, working papers, and editorials were also excluded as such publications are deemed to go through a less rigorous review process before publication. Previous review papers were also excluded to get an unbiased review of original research articles. These exclusion criteria helped in restricting the research process to retain focus on the research problem. The review has included only those articles relating to studies that contained topics relating to the analysis of the life cycle energy of buildings. Articles in conference proceedings were included due to their relevance. Both qualitative and quantitative studies were included in the review, as most of these studies were duly backed up by case studies. Articles focussing on life cycle assessment (LCA) of products pertaining to environmental impact assessment under impact categories like global warming potential, water consumption, eco-toxicity, eutrophication, resources consumption, and cumulative energy demand (ISO, 2000) were also included as life cycle energy analysis is a specific type of LCA where energy is the main focus or impact category of assessment.

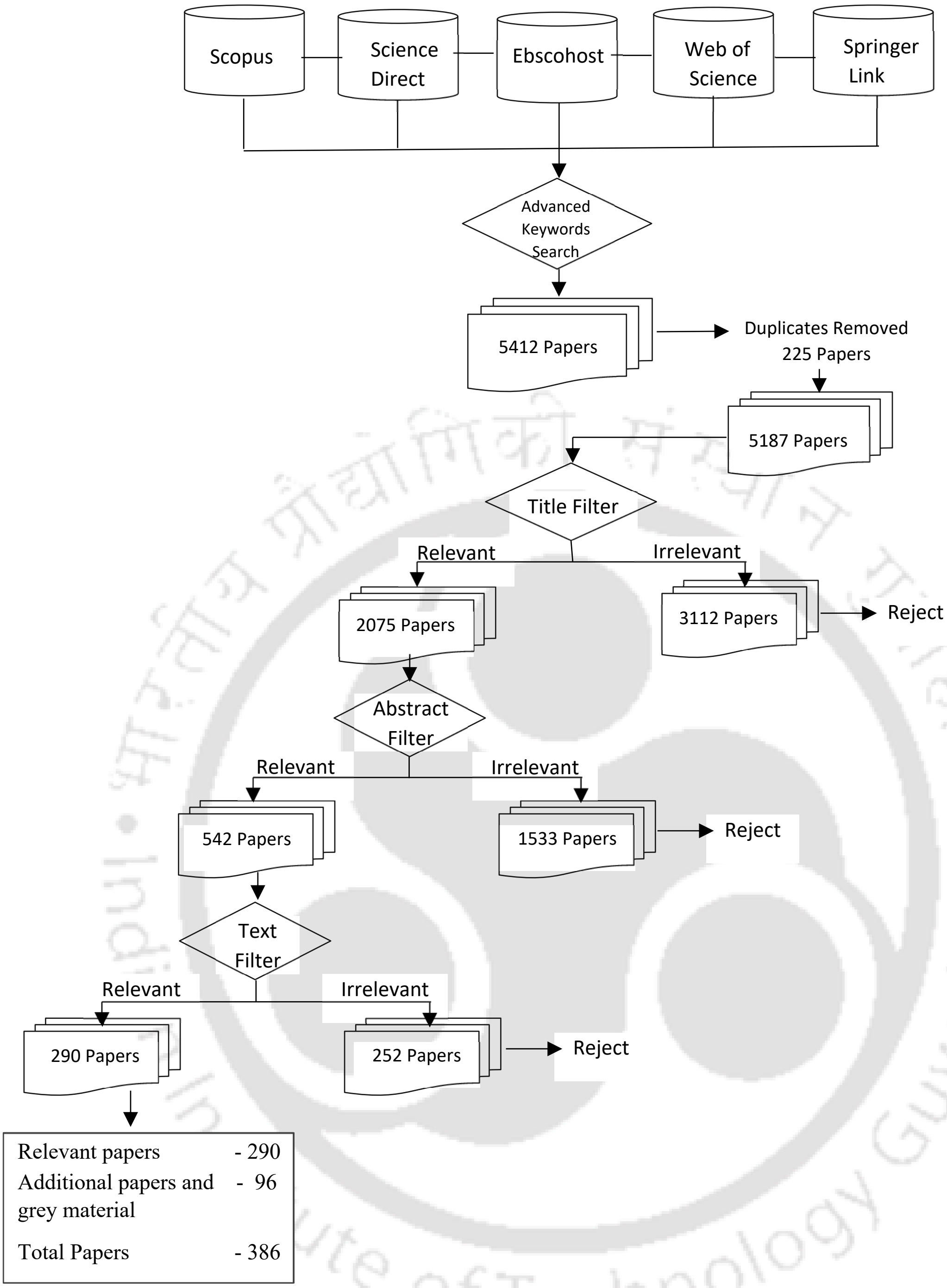


Figure 2.2 Material selection process (Adapted from Igarashi et al. (2013))

2.3.2 Material Evaluation

A total of 5142 article titles were identified after an advanced search of the five databases. Duplication of articles across the five databases was removed, and the selected papers were put through three filters: title analysis, abstract analysis, and text analysis. At the end of the text analysis filter, 290 relevant articles were chosen. The manner in which these articles are distributed across the five databases is shown in **Table 2.1**. The maximum number of publications was collected from the Scopus database, while the search through SpringerLink resulted in the least number of articles.

Table 2.1 Summary of the publication selection process

Database	Basic Keyword search	Advanced keyword search, including duplicates	1st filtration Title filter after removal of duplicates	2nd filtration Abstract filter	3rd filtration Text filter (Studies selected)	Percent selected After 3rd filter (%)
Scopus	2390	1027	460	147	97	32
Science Direct	5313	1575	632	135	75	28
Web of Science	2770	683	325	115	71	24
EBSCOhost	53839	1782	523	89	37	13
SpringerLink	34852	345	135	56	10	3
Total (No. of papers)	99164	5412	2075	542	290	100

Amongst these databases, the top five publishers are Elsevier, Taylor & Francis Limited, Sage Publications Limited, Springer and the American Society of Civil Engineers. **Figure 2.3** shows the percentage share of the articles amongst the publishers. The maximum number of relevant articles were published by Elsevier, while the American Society of Civil Engineers published the least number of relevant articles under this review.

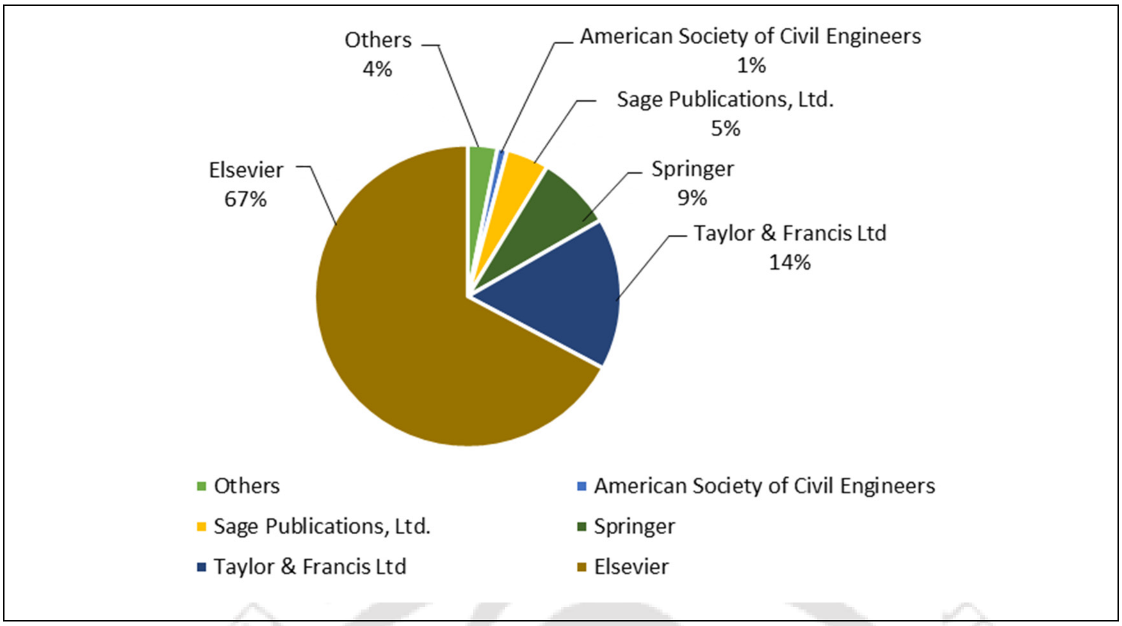


Figure 2.3 Percentage share of papers under review across publishers

Similarly, amongst journals, '*Energy and Buildings'* published the maximum number of relevant articles across all journals in the combined database, followed by *'Building and Environment'*. The distribution of papers in the top ten journals of the combined database is shown in **Figure 2.4**.

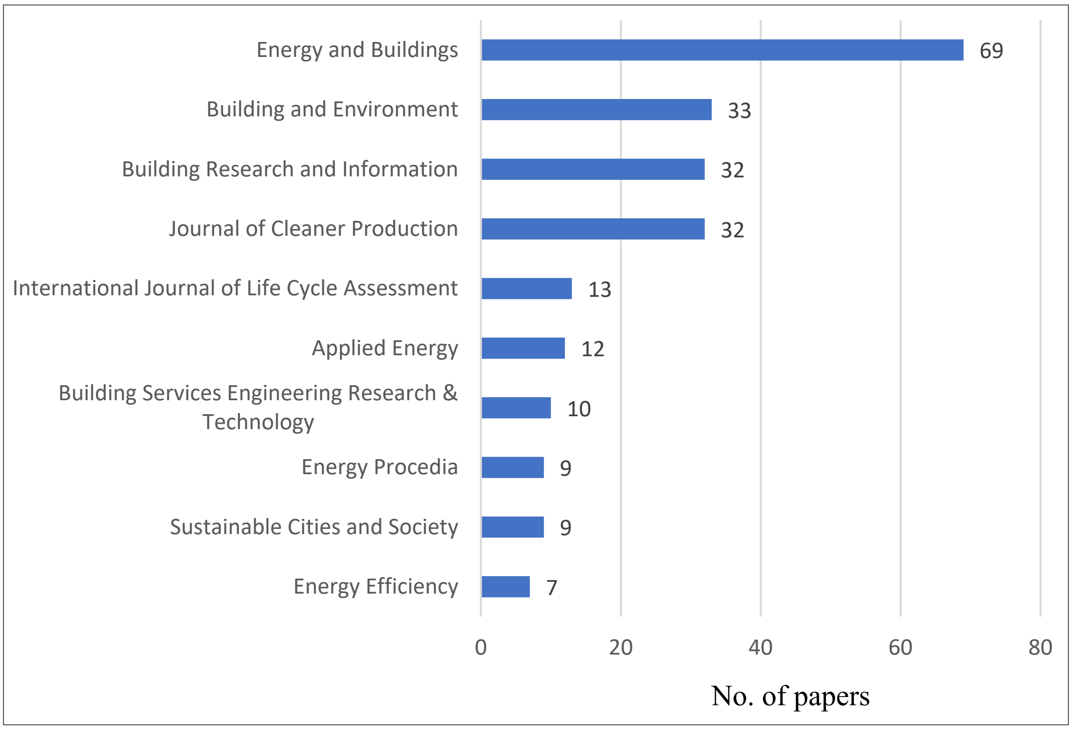


Figure 2.4 Distribution of papers in the top ten Journals of the combined database

The list of the top 20 most cited papers in past studies, along with Publishing journals, is shown in **Table 2.2.** In this list, *'Building and Environment'* contained the maximum number of most cited papers, closely followed by '*Energy and Buildings',* which may indicate the authors' preference and the relevance for publishing articles on building energy analysis in these journals.

Most studies on buildings' life cycle energy have originated from Europe, followed by publications from Asia and North America. Amongst these countries, most studies were undertaken by researchers from the USA, followed by the UK and China. Furthermore, most researchers (around 90%) have opted to conduct the studies within the country of research origin. This could be attributed to the ease of availability of data and the long timespan required for data collection over the lengthy building construction process.

The distribution of articles on studies relating to the heating and cooling of buildings across the countries is shown in **Figure 2.5**. Maximum number of publications on heating originated from Europe (68 %), followed by Asia (19 %). Similarly, the maximum number of studies on combined heating and cooling originated from Europe (51 %), followed by Asia (24 %). Also, Europe published a higher proportion of papers on heating only with respect to the total number of articles published on combined heating and cooling. On the other hand, a significant amount of research on cooling was related to Asia (60 %), followed by Africa (13 %) and North America (13 %). Furthermore, the scope of the building considered in analysing the life cycle energy intensity also varied. Most of the previous studies have selected the whole building as the scope for analysis, followed by taking building materials and building components. On the other hand, very few studies have conducted research at the city, region/state and national or global scale, probably due to the non-availability of requisite data to the researchers.

Table 2.2 List of top 20 most cited papers in past studies

S. No.	Article title	Source /Journal title	No. of times cited	Author reference
1	Life cycle energy and environmental performance of a new university building: Modelling challenges and design implications	Energy and Buildings	426	Scheuer et al. (2003)
2	A low energy building in a life cycle - Its embodied energy, energy need for operation and recycling potential	Building and Environment	389	Thormark (2002)
3	Introducing the prebound effect: the gap between performance and actual energy consumption.	Building Research & Information	379	Sunikka and Galvin (2012)
4	Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	Building and Environment	331	Bribián et al. (2009)
5	Life-cycle energy use in office buildings	Building and Environment	306	Cole and Kernan (1996)
6	Greenhouse gas emissions due to concrete manufacture	International Journal of Life Cycle Assessment	268	Flower and Sanjayan (2007)
7	The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings	Energy and Buildings	267	Blengini and Di Carlo (2010)
8	From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)	Energy and Buildings	252	Hernandez and Kenny (2010a)
9	Sustainability assessment in the construction sector: Rating systems and rated buildings.	Sustainable Development	249	Berardi (2012)
10	The effect of material choice on the total energy need and recycling potential of a building	Building and Environment	219	Thormark (2006)
11	Life cycle assessment: A case study of a dwelling home in Scotland	Building and Environment	219	Asif et al. (2007)
12	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy	Building and Environment	216	Blengini (2009)
13	Genetic-algorithm based approach to optimize building envelope design for residential buildings	Building and Environment	202	Tuhus-Dubrow and Krarti (2010)
14	Energy use during the life cycle of single-unit dwellings: Examples	Building and Environment	187	Adalberth (1997b)
15	A life-cycle energy analysis of building materials in the Negev desert	Energy and Buildings	183	Huberman and Pearlmutter (2008)
16	Using national input–output data for embodied energy analysis of individual residential buildings.	Construction Management & Economics	181	Treloar et al. (2001c)
17	Comparative life cycle assessment of standard and green roofs	Environmental Science and Technology	160	Saiz et al. (2006)
18	Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock	Energy and Buildings	155	Dascalaki et al. (2011)
19	Energy use during the life cycle of buildings: A method	Building and Environment	148	Adalberth (1997a)
20	Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm	Building and Environment	141	Fesanghary et al. (2012)

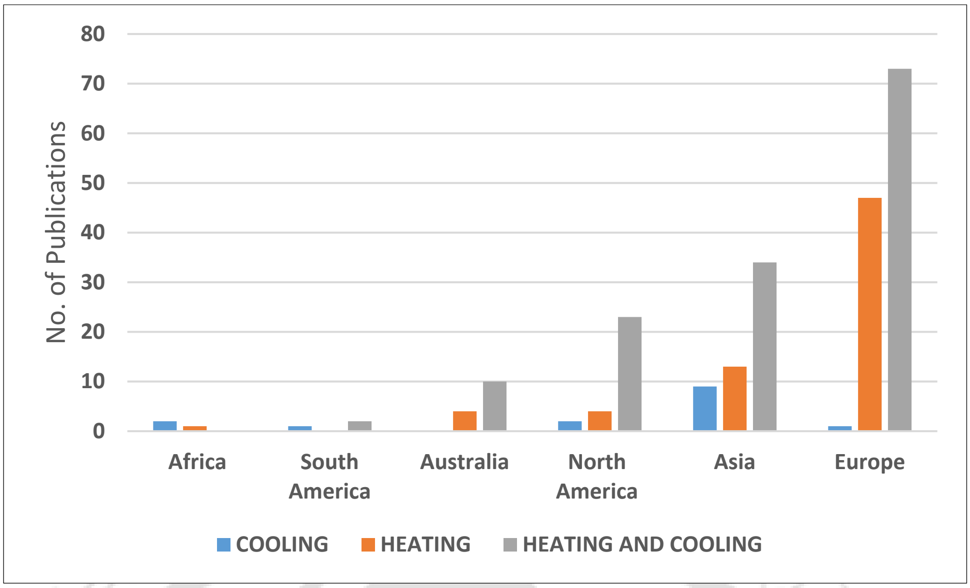


Figure 2.5 Geographic origin of past studies on heating and cooling of buildings

Regarding the research strategy adopted by the researchers, the majority of the studies, i.e., more than 70%, have preferred to work on case studies, about 15% of the studies were conceptual, and nearly 13% of the studies adopted a combination of conceptual and case-study approach. The reason for preferring the case studies approach seems justified since case studies can be treated as acid tests of theoretical concepts, as they truly depict the complexities and dynamics of the real world. Finally, experimental and experimental-cum-case study methods were not very widely used.

Studies on energy analysis of buildings can be broadly classified into two categories from a functionality perspective: residential and non-residential buildings. Non-residential buildings can be further sub-classified into office, commercial, educational, industrial, and special function buildings such as hospitals, lodges and hotels. It could be observed from the review that most of the studies on energy analysis have focused on the energy analysis of residential buildings **(Figure 2.6).** The reason for this focus could be that residential buildings account for approximately 75 % of the total energy consumption in the building sector. Another reason for focusing on residential buildings is the opportunity to limit global warming to “well below 2°C” target by 2040, as mandated by the Paris Agreement of 2015, by striving to achieve an average heating and cooling demand of 50 kWh/m^2/year in industrialised and transition economies (IEA, 2016).

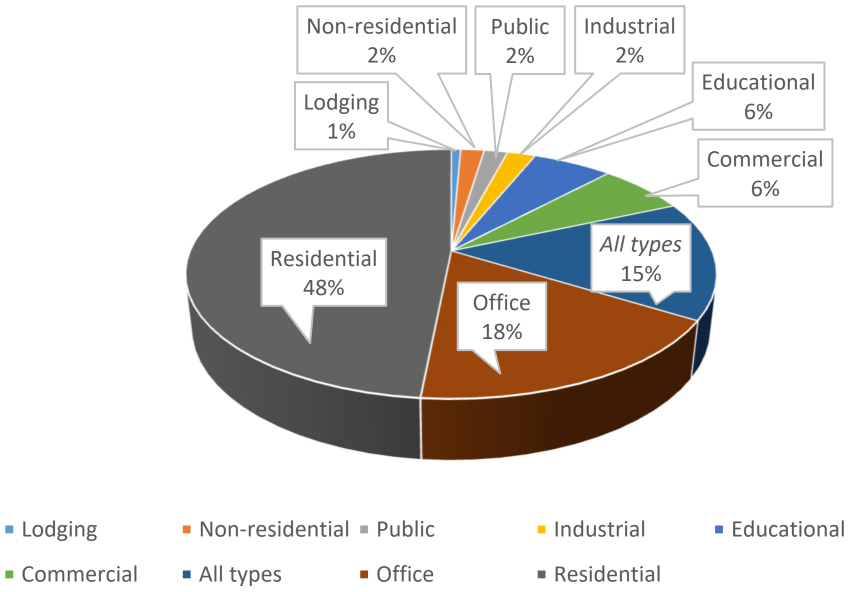


Figure 2.6 Share of types of buildings considered in past studies

The spread of types of buildings across a number of storeys in past studies is shown in **Figure 2.7.** A maximum number of studies is concentrated in the range of 1 to 4 storeys high building space. Studies on buildings with more than ten storeys height, particularly industrial, educational and public buildings, are limited as they would not be functionally convenient.

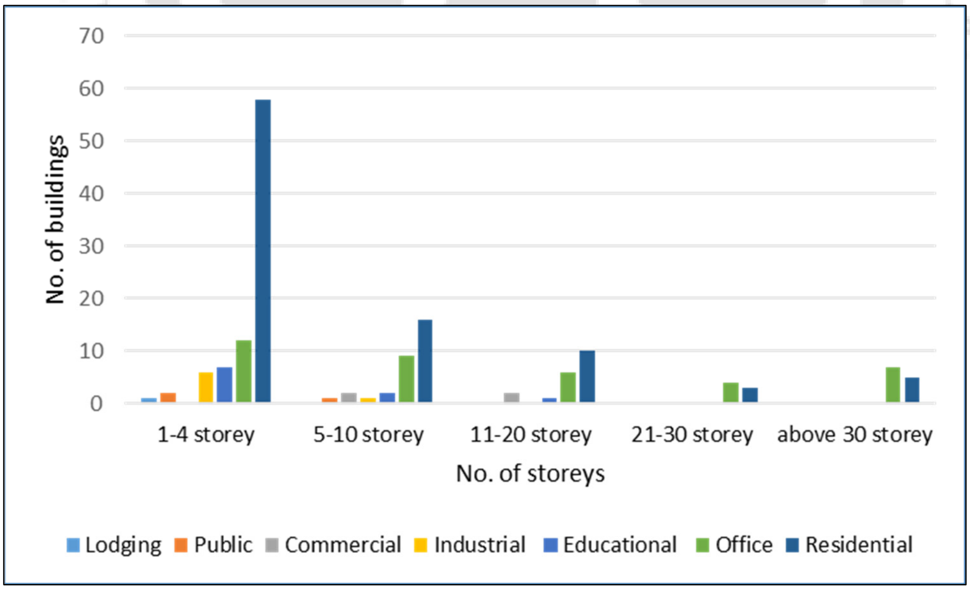


Figure 2.7 Spread of types of buildings across No. of storeys in past studies

2.4 SIGNIFICANT OBSERVATIONS FROM REVIEW OF LITERATURE

2.4.1 Selection of system boundaries for energy analysis of buildings

In the past, many researchers have attempted to carry out LCEA of varying components of building projects. The Life cycle energy (LCE) estimates of some of the earlier studies have shown large variation from 37 kilowatt hours/m^2/year (kWh/m^2/year) (Leckner & Zmeureanu, 2011) to 512 kWh/m^2/year (Pullen, 2000a) in case of residential buildings. Similarly, the results of LCEA of non-residential buildings have also shown variations from 114 kWh/m^2/year (Voss & Musall, 2012) to 1170 kWh/m^2/year (Scheuer et al., 2003). The reasons for such large variation in LCE can be grouped into two categories, viz., methodological parameters and data quality parameters. Methodological parameters consist of: a) system boundaries, b) method of energy estimation, and (c) type of energy considered (primary energy vs. final energy). On the other hand, data quality parameters include a) age of data, b) source of data, c) data accuracy and completeness, and d) geographical representation. *Out of the above, system boundary selection (Dixit et al., 2013; Horvath, 2004) and geographical representativeness (Doh & Panuwatwanich, 2014; Khasreen et al., 2009) are two of the most critical parameters causing the largest variation in the results of LCE estimations.*

The system boundaries refer to the life cycle stages and scope of the building project considered for LCEA. The system boundary establishes the material and energy inputs and outputs of a system. Dixit (2017b) has argued that the average life cycle EE variations of 6%, 10%, 25% and 3% could be caused by the non-inclusion of transportation, construction, recurrent, and demolition energy, respectively. Past studies have mainly focussed on the building portion only, and all other building project components, such as MEP services (Basbagill et al., 2013) and site development features, are rarely included in the scope of the study. It has been established that the non-inclusion of building project components such as MEP services, furniture items and home appliances can cause a sizeable variation (Dixit, 2019; Venkatraj et al., 2020) in EE estimates of the buildings.

The life cycle of a building can be broadly classified into three stages, for instance Pre-occupation stage, Use/ Operation or Occupation stage, and End of life/demolition/post-occupation stage (Alam et al., 2019; Bourdeau et al., 2019; Tavares et al., 2021; Vilches et al., 2017). These stages can be further subdivided into several sub-stages (Sosa et al., 2017; Wang et al., 2018). The amount of energy consumed by a building also depends on other factors, viz., building design, climate, type of building material used for construction, the intended function of the building, occupant behaviour, Heating, Ventilation and Air Conditioning (HVAC) equipment installed, and appliances used by the occupants.

Past studies were found to differ in the selection of system boundaries for energy analysis of buildings. The distribution of literature over stages of the building life cycle and timeline is shown in **Figure 2.8.** The maximum number of studies have been carried out on energy analysis during the operation stage of buildings, followed by the pre-occupation stage and complete life cycle of buildings. Also, in the pre-occupation stage, very few authors (about 11 per cent) accounted for energy inputs during the design sub-stage, and the reasons for the above trend are as follows. Firstly, conventional buildings consume more energy during the operation stage than the pre-occupation and end-of-life stages. Secondly, as modern buildings are increasingly designed for higher thermal comfort and enhanced energy efficiency, they involve the use of building materials such as insulation panels with higher embodied energy intensity. Consequently, the proportion of embodied energy with respect to operation energy is on the rise. Thirdly, more studies are resorting to LCA and LCEA of buildings due to increasing climate change and sustainability awareness. Very few studies were found to have focused on the end-of-life stage, probably either due to a lack of reliable data (Hong et al., 2016; Ortiz et al., 2009; Tatiya et al., 2018) or due to the assumption that very low proportion (Karimpour et al., 2014; Zeng & Chini, 2017) of energy is consumed during demolition stage in conventional buildings. However, as new buildings are being designed for low energy demand during the operation stage, the relevance of reduction in embodied energy consumption during the end-of-life stage cannot be overlooked any further.

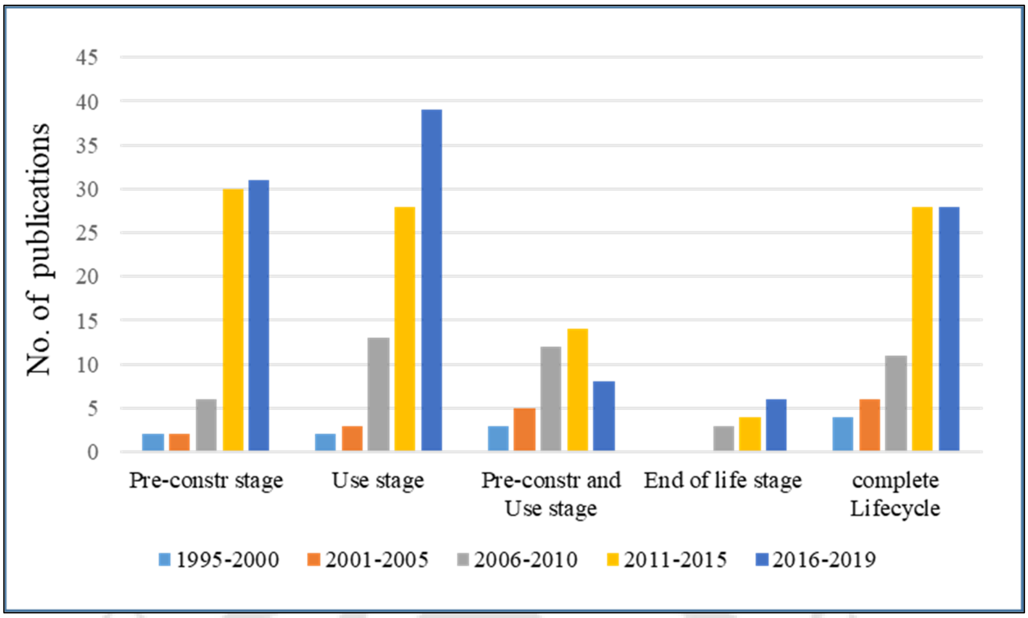


Figure 2.8 Distribution of literature over stages of building life cycle and timeline

2.4.2 Geographical representativeness

Geographical representativeness pertains to the use of energy data of the country where the building is located. Large differences exist between the economies, energy mix, energy production and distribution efficiencies, energy tariffs, efficiencies of manufacturing industries, transportation distances, and construction practices of countries. Therefore, the use of energy data from other countries can lead to variation and errors in EE estimation (Dixit et al., 2014; Hammond & Jones, 2010; Menzies et al., 2007).

2.4.3 Relevance of building components and building material

The building envelope is reported to be the most important part of a building from the operational energy demand considerations. The building envelope comprises the foundation, external walls, doors, windows, floor and roof. Most of these studies have focused on external walls, curtain walls, windows and roof of a building.

The operational energy consumption of a building is largely dependent on the thermal characteristics of its building envelope (Volf et al., 2018). In a study by Dimoudi and Tompa (2008), the structural building materials, viz., concrete and reinforcement steel, represented the highest share in the total embodied energy of the examined buildings, closely followed by the embodied energy of the building envelope materials. In addition, Saiz et al. (2006) have emphasised that green roofs are highly effective in energy conservation due to their low solar absorptance, resulting in lower surface temperature and consequent reduction in the heat flux through the roof.

The use of secondary material, such as Wood-Plastic Composite (WPC) for plank products, and secondary concrete, i.e., crushed concrete and bricks from demolished buildings, can result in reducing embodied energy consumption. Therefore, public policies that promote the use of circular building materials, reuse and recycling of material from construction and demolition waste, and incentivise waste collection and recovery markets can also bring down the embodied energy of construction material (Nußholz et al., 2019).

2.4.4 Service life of building material - implications

The service life of a building material will depend on its raw material composition, process of manufacturing, climatic conditions and type of usage in a building. Thus, different materials used in building production would have a different life. The life of some important building materials considered in past studies is depicted in **Table 2.3**. This review reveals that no consensus is visible amongst researchers on the stipulation of the useful life of a building material. For instance, the life of reinforcement steel is seen to vary from 50 years (Ghaemi & Amidpour, 2019), (Chau et al., 2007) to 120 years (Marsh, 2016) **(Table 2.3)**. The life span of a building would also be determined by the life of important building materials, especially materials such as concrete, reinforcement steel, and structural steel and structural timber components in steel and timber constructions, respectively.

Therefore, careful selection of building material is important at the design stage due to its environmental footprint during all stages of a building life cycle. Unfortunately, the information provided by the manufacturing industry on energy labelling of construction material in terms of the Environmental Product Declaration (EPD) is either limited (Scheuer et al., 2003) or lacks standardisation (Shadram et al., 2016).

Table 2.3 Life of important building materials considered in past studies (years)

Ser	Building material ↓ | Ref →	Ghaemi and Amidpour (2019)	Marsh (2016)	Iddon and Firth (2013)	Ding (2007)	Adalberth (1997a)	Scheuer et al. (2003)	Chau et al. (2007)
	Author's source of data →	Seiders et al. (2007)	Aagaard et al. (2013)	Design life	Langston (1994), Kirk and Dell'Isola (1995), AIQS (2002)	SABO (1992)	UM, Kirk and Dell'Isola (1995)	Scheuer et al. (2003), Adalberth (1997a), ASHRAE (2003)
	Structural							
1	Reinforcement steel	50	120	-	-	-	75	50
2	Concrete	-	120	120	-	-	75	50
3	Structural steel	-	-	-	-	-	75	50
4	Structural timber	-	120	-	-	-	-	-
	Non-structural							
5	Brick	60	-	120	60	-	-	50
6	Concrete block	-	-	120	-	-	-	-
7	Roof tile	-	-	60	30	30	-	-
8	Insulation material	-	120	-	-	50	75	50
9	Floor tiles-ceramic	60	-	60	-	-	-	10
10	Glass	25	-	-	-	-	-	45
11	Paint	-	15	5	10	10	5	10

UM- Architectural, Engineering and Construction Department, University of Michigan

AIQS-Australian Institute of Quantity Surveyors, SABO-Swedish Association of Public Housing Companies

2.4.5 The life span of buildings

In the absence of any laid down standards or guidelines, past researchers have assumed various life spans of buildings ranging from 25 to 120 years. A maximum number of past studies considered a building life span of 50 years, followed by 60 and 100 years, with very little sprinkling of other life spans. Certain countries, such as Iran, have a short life span of buildings (25 years) due to low quality basic construction materials (Ghaemi & Amidpour, 2019). Other non-technical reasons for the short life span of buildings include appreciation of land value, change in functional requirements, low building energy efficiency, and lack of timely maintenance of buildings (Kestner & Webster, 2010). The building life span has a bearing on the annualised embodied energy, operation energy and hence the life cycle energy of a building. For instance, the recurrent embodied energy of a building will increase with the increase in life span of the building due to an increase in number of repairs, maintenance, and material replacements. This emphasises the necessity for standardisation on building life span for better comparability amongst different studies.

2.4.6 Absence of data archiving and data sharing mechanism

Most of the reviewed articles relied on individual sources of data collection (e.g., contractors) for building energy related studies, and the availability of institutionalised data banks on buildings is rarely reported. Though the data is generally collected, it is rarely shared by the owners for use by policy makers and analysts outside the organisation (Hartenberger & Lorenz, 2019). The recently launched "Building Passport" initiative by RICS School of Built Environment (RICS-SBE) Amity University, India, in collaboration with Global Alliance for Buildings and Construction (Global ABC), aims at developing a digital data platform on buildings from construction to demolition stage for use by stakeholders (GlobalABC, 2019). Some other initiatives for the improvement of data availability are Annex 70 (IEA), C40 Cities and ICLEI – Local Governments for Sustainability carbon Climate Registry (cCR) (Wilmsen & Gesing, 2016). Though India has enacted the Real Estate Regulation and Development Act, 2016 (RERA, 2016), the mandatory data required to be uploaded for project registration is inadequate for any serious research (Hamilton et al., 2017). These initiatives are a good beginning, but we have a long way to go. Since the availability of data is at the heart of research work, researchers need to have greater access to local authority databases of building construction, approvals and compliance. Therefore, one suggested option is that the sharing of building construction and energy use data by builders, project management consultants (PMCs) and facility management agencies could be mandated by policy framework, especially for projects funded by public sector financial institutions.

2.4.7 Methods used for estimation of building energy

Embodied Energy

Methods used to estimate EE in past studies under review can be classified into five categories, i.e., inventory analysis, LCA/life cycle cost analysis (LCCA)/LCEA, mathematical tools/calculations, experimental investigations and propriety tools/models, as shown in **Table A-1** of **Appendix A.**

Inventory analysis remains the primary method of EE estimation across most publications in this review. A sizeable number of past studies have fallen back on readily available life cycle inventory (LCI) databases such as Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011), Eco-invent (Wernet et al., 2016), and U.S. Life Cycle Inventory (U.S.LCI) of National Renewable Energy Laboratory (NREL, 2012) for estimation of EE of buildings. Additionally, a large number of researchers have used various opensource or country specific LCA software/tools based on ISO 14000 series (Environmental Management/Environmental Labelling) such as ATHENA Impact Estimator (Athena, 2021), SimaPro (PRé Sustainability, 2021), SimStadt (Nouvel et al., 2015), and Eco-Indicator (Pushkar, 2014) which are predominantly sustainability assessment tools having their integral LCI databases. Other LCA based methods include LCCA and LCEA, which are restricted to the calculation of EE of buildings during their entire life cycle. However, significant drawbacks have been observed in the usage of existing life cycle inventory databases and LCA tools in the extant literature, such as non-inclusion of all stages of building life cycle (Guan et al., 2016; Haapio & Viitaniemi, 2008), lack of transparency (Khasreen et al., 2009; Robertson et al., 2012), and incompleteness of data (Ristimäki et al., 2013). Additionally, these databases and tools suffer from errors on account of geographical and temporal relevance, averaging of energy and environment coefficients from secondary sources (Guan et al., 2016; Stephan et al., 2019). The distribution of reviewed papers as per methods used for embodied energy estimation is shown in **Figure 2.9**.

Among the most widely proliferated inventory analysis methods are process analysis, input/output analysis and hybrid analysis. The process-based embodied energy (EE) is considered more accurate and reliable (Stephan et al., 2012). However, it is reported to be impracticable and incomplete due to truncation of system boundaries and exclusion of many upstream processes, for example, capital energy inputs into plants and machinery used in building material production (Pullen, 2000b).

The input/output-based analysis makes use of economic data of money flow among various sectors of industry in the form of input/output tables published by the national governments and transcribes the economic flows into energy flows by applying average energy tariffs on the cost of the products (Crawford & Treloar, 2005). This method suffers from problems such as the assumption of homogeneity and proportionality, errors and uncertainty of economic data (for example, energy tariff and product cost), and aggregation and grouping of sectors.

The hybrid method starts with process analysis of readily available energy input data of the final production stage and one more stage in the upstream and then substitutes it with the input/output method when it is difficult to obtain reliable and consistent information regarding complex upstream processes (Lenzen, 2000). Out of the two types of hybrid methods, viz., process based hybrid analysis and input-output based hybrid analysis, the latter (input-output based hybrid analysis) encompasses the entire system boundary and is considered relatively comprehensive and complete (Chang et al., 2014; Crawford et al., 2003).

Variations in energy estimation may occur due to the type of method used for energy calculations. For example, EE estimation using the process analysis method has shown underestimation ranging from 59% to 69% as compared to EE estimation when I-O based hybrid analysis method was used in 4 case study buildings investigated by Crawford (2008). Furthermore, the mean embodied energy in developed countries is reported to be lower than that in less developed countries due to differences in the economic situation, technical reasons, and socio-political factors (Ghaemi & Amidpour, 2019).

Also, a strong correlation has been found between the capital cost of a building and initial EE at the project level, which is also the underlying principle of the input/output method (Langston, 2008). Since real estate enterprises thrive on profit maximisation goals, LCCA would need to be given due importance while considering building design and retrofitting strategies for the improvement of building performance.

Some researchers have used experimental methods such as action research to highlight the importance of good site management practices in reducing the EE of buildings. Some others have documented energy savings due to the use of alternative construction methods, such as the post-tensioned construction method for slabs and beams.

Some studies have also reported that variation in recurring embodied energy during the operation stage of buildings could occur due to differences in the type of building, the useful life of building material and components (Rauf & Crawford, 2015), degree of repair and maintenance required (Mourao et al., 2019), the life span of buildings, and the system boundaries (Mourao et al., 2019) considered. For instance, Utama and Gheewala (2009) reported annual REE values between 0.1% to 0.3% of IEE for residential buildings as the study considered low replacement factor only for a few building components. On the other hand, Pullen (2000a) found the annual average REE to be 1.2% of IEE as it considered a more comprehensive schedule for repair. Maintenance and replacements are based on inputs from the building occupants.

Operational Energy

Methods used by researchers in past studies for operational energy estimation can be classified into six categories, i.e., Energy Simulation Tools/Software, LCA/LCC/LCEA, Mathematical Tools/Calculations, Miscellaneous (Misc) Methods, Proposed Framework, Proprietary Tools/Models as shown in **Table A-2** of **Appendix A.** The distribution of reviewed papers as per methods used for energy estimation is shown in **Figure 2.9**

Out of all the above methods, energy simulation tools/ software has found the highest acceptability amongst researchers, wherein energy simulation engines, e.g., EnergyPlus, DOE.2-2 and eQuest in conjunction with a BIM software (REVIT, ArchiCAD, and Archsim in Grasshopper or Sketchup) and a graphical user interface (GUI) such as Green Building Studio or OpenStudio, have been used extensively. Of late, a commercial software 'DesignBuilder v5' has developed a built-in BIM module for use in conjunction with the EnergyPlus simulation engine, but the licenses are quite expensive. Sustainability assessment tools such as SimaPro, Ecotect and some country specific simulation software have also been found popular, especially when the main focus of research is on the environmental impact of building construction.

In addition, large variation has been observed in the findings of operating energy investigations conducted by past researchers. Some of the primary reasons for this variation could be attributed to differences in the types of buildings, the use of different methods for energy estimation, and different climates where the buildings are located (Andrić et al., 2019). For instance, Ramesh et al. (2010) found the normalised OE of office buildings in general to be higher (250-550 kWh/m^2/y) than that of residential buildings (150-400 kWh/m^2/y). Aste et al. (2015) revealed that using static methods in place of dynamic methods for estimating energy demand could result in a variation of up to 26% in the predicted values due to the dynamic thermal behaviour of the building envelope. Climate change is another factor that could add to the variability of results, for instance, Berardi and Jafarpur (2020) predicted that the heating energy requirement could decrease by an average of 25% and the cooling energy demand could increase by an average of 70% in Toronto, Canada due to future climate changes. Therefore, these factors should be considered while comparing the results of various studies. Consequently, operating energy efficiency should be compared only for similar types of buildings located in similar climatic zones for a realistic assessment.

Demolition Energy

Demolition energy (DE) of a building is the energy consumed during the post-occupation stage or End of Life (EOL) stage of a building. mechanical demolition, deconstruction and implosion. Mechanical demolition is equipment intensive and faster, but since separation of waste is difficult, most of the demolition waste has to be sent to landfill. On the other hand, deconstruction is slower, being more labour intensive, but affords easy segregation of waste, thereby affording a higher proportion of waste to reuse and recycling, which enables recovery of cost and energy (Pun et al., 2006). Therefore, hybrid demolition, which combines the benefits of mechanical demolition and deconstruction, would be more economical. However, as the use of mechanical equipment would not be practical, high-rise building demolition typically involves controlled explosion.

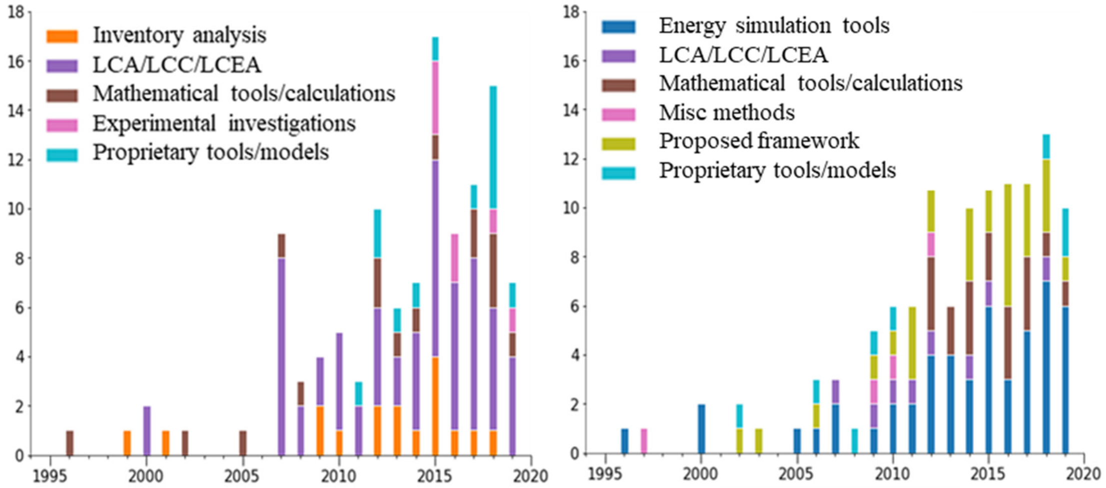
Methods used by researchers in past studies for DE estimation can be classified into four categories, i.e., Field measurements, LCA and Building Information Modelling (BIM), Mathematical Tools/Models, and Proposed Framework, as shown in **Table A-3** of **Appendix A**. Out of the reviewed literature, only a miniscule number of articles dealt with estimation of demolition energy, indicating a requirement for additional studies on demolition energy **(Figure 2.9)**.

Life Cycle Energy

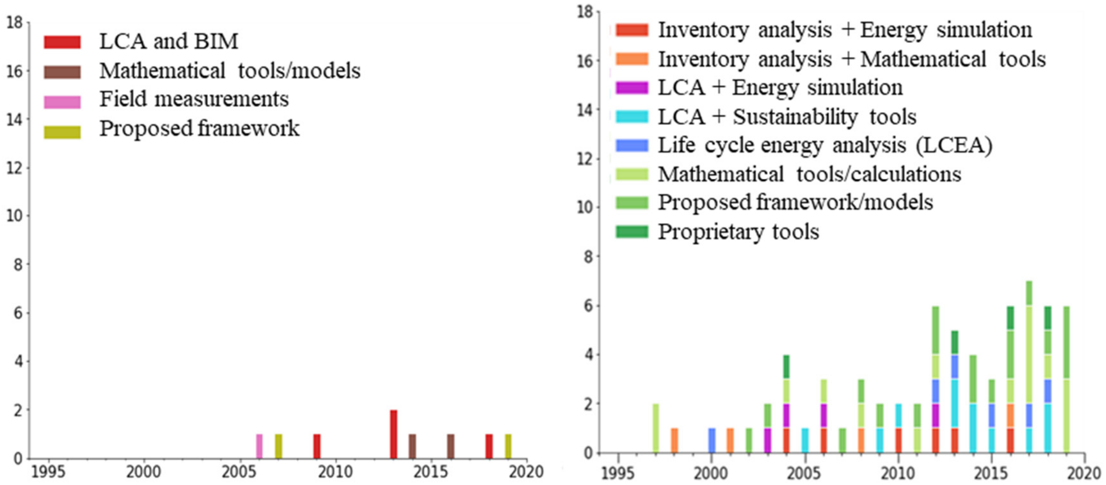
The life cycle energy (LCE) of a building is the energy consumed by the building during its entire life cycle from the pre-occupation stage to the EoL stage. Methods used by researchers in past studies for life cycle energy estimation can be classified into various categories, i.e., Inventory Analysis + Energy Simulation Tools, Inventory Analysis + Mathematical Tools, LCA + Energy Simulation Tools, LCA + Sustainability Tools, LCE Analysis, Mathematical Tools/Calculations, Proposed Framework/Models and Proprietary Tools, as shown in **Table A-4** of **Appendix A**.

Past studies indicate that LCE consumption of buildings can be minimised through the proper selection of building materials and services in the early design stages. Building operation uses the largest share of energy in the building life cycle, wherein cooling and heating systems strongly influence the building energy consumption. Also, the short duration of the building construction stage affords better evaluation of upstream processes, as compared to the operation stage of a building, which generally lasts more than 50 years. During this long phase, building function, energy mix, and energy generation methods may undergo a change, thereby introducing uncertainty in the use of LCA modelling for the downstream processes (Dong & Ng, 2015).

Estimation of LCE of buildings involves a combination of various methods enumerated above for the calculation of EE, OE and DE based on the purpose of a study (**Figure 2.9**). Field measurement or site survey methods, although high on the accuracy scale, do not facilitate LCEA at the design stage, and these can be used either for planning HVAC systems for new buildings or for conducting energy audits for retrofitting existing buildings for improvement of energy efficiency. On the other hand, methods using a combination of BIM and energy simulation tools have the advantage of enabling LCEA at the design stage for finding optimum energy design alternatives. In fact, a holistic approach should be to use the energy simulation tools to select the optimum design parameters after evaluating feasible design alternatives. Thereafter, field measurements can be taken up to assess the actual energy performance of the buildings with respect to the designed performance. The learnings from the performance gap between the designed and actual performance can be used to minimise the performance gap in the future design of the buildings.



(a) Embodied energy (b) Operating energy



(c) Demolition energy (d) Life cycle energy

Figure 2.9 Incidence and type of methods used for energy analysis of buildings:

Recently, some studies have used new methods such as Multi-Objective Optimisation (MOO), Multi-Region Input-Output (MRIO) method and Multi-Criteria Decision Making (MCDM) method for the calculation of energy demand during various stages of the building life cycle. The I-O-based methods do not account for variations in energy intensities of building products imported from other countries. Therefore, researchers have used the Multi-Region Input-Output (MRIO) method in place of the I-O methods for the estimation of the embodied energy of buildings (Hong et al., 2019; Hong et al., 2018). MOO is found useful for design optimisation in cases of competitive objective functions, for instance, LCC and LC CO_2 emissions (Fesanghary et al., 2012) or LCE and LC CO_2 emissions (Taghizade et al., 2019). Similarly, MCDM can be adopted for the evaluation of design alternatives based on multiple criteria from energy performance considerations (Gupta et al., 2017; Kabak et al., 2014; Talang & Sirivithayapakorn, 2018).

The most critical observation is that there are no explicit guidelines or standards for the conduct of LCEA of buildings, and a number of methods were used for the estimation of LCE, thereby leading to further variations in the results. Therefore, there is a need for standardisation of the LCEA. Additionally, as the economy, manufacturing processes, and energy mix of one nation differ considerably from the other, the LCEA process needs to be streamlined at the national level.

Furthermore, the estimation of building LCE presently involves the use of multiple inventory databases, the creation of building models, and a mandatory user interface for energy simulation tools. Thus, the existing LCEA methods are resource-intensive in terms of time and cost and do not motivate building designers to conduct energy analysis of buildings as part of their work. This calls for the need for a single, comprehensive, integrated, and country specific tool for seamless and cost-effective estimation of the LCE of buildings and its wider embracement by the AEC industry.

2.5 SUMMARY OF LITERATURE REVIEW

The literature was reviewed in two parts, i.e., a scoping literature review followed by a systematic literature review. The scoping literature review surveyed various instruments employed for exercising control over the energy performance of buildings across the globe. Most nations have set MEPS in terms of building codes and standards for conventional buildings, which are mandatory in nature. These building codes were supplemented with energy conservation building codes (ECBCs), which were applicable to buildings above a laid down building floor area or buildings above a given connected load. The implementation of ECBCs was voluntary in some countries but mandatory in others. In addition to building codes and ECBCs, most nations have come up with green building certification systems. However, it was found that green building certification does not necessarily result in energy demand lower than that of a similar conventional building, and green building certification appeared to be merely a means of deriving commercial advantage over competitors. Also, a number of past studies focussed on individual stages of the building life cycle, but as the various stages of the building life cycle are interdependent, there is a need to consider the complete life cycle of the building while carrying out the energy analysis.

After ascertaining the need for life cycle energy, a systematic literature review was conducted from 290 publications selected from five databases through a rigorous approach. The findings of the systematic literature review helped in gaining insight into publication trends and the relevance of critical factors that influence the outcome of building energy analysis, such as building life span, service life of building material, functional usage of the building, height of the building, system boundaries considered, geographical representativeness of data utilised, availability of data sharing framework, and type of method used for building energy analysis. Out of the above, system boundary selection is the most important factor that leads to maximum variation in the results of building energy analysis.

The following research gaps were identified in general during the review of the literature:

(a) Non-inclusion of all stages of the building life cycle.
(b) Non-inclusion of the complete scope of the project.
(c) Lack of research on energy analysis of high-rise residential buildings.
(d) Lack of geographical representativeness for estimation of embodied energy.
(e) Inadequate coverage of energy analysis on end-of-life stage of buildings in past studies.

2.6 RESEARCH PROBLEM

A building project system may comprise a primary or a core building and subsidiary or support facilities that enable the core building to perform its designated functions. The primary building by itself is not capable of meeting its designed objectives. These support facilities could consist of one or more entities such as site development features (internal roads, boundary wall, street lights, drainage system, and arboriculture), power supply system, water supply system and sewage treatment plant, depending on the site conditions, size of the building project and the availability of municipal infrastructure. Improvements in building codes and environmental standards have resulted in a reduction of energy demand of buildings during the operation phase. Also, embodied energy forms an integral and a sizeable part of the life cycle energy of buildings. System boundary selection is the key parameter that causes problems of inconsistency, inaccuracy and incompleteness of data in embodied energy results (Horvath, 2004; Dixit et al., 2012; Davies et al., 2014). As observed from the review of literature, most of the past studies have selected very narrow system boundaries while estimating embodied energy or operating energy of the buildings, leading to unrealistic assessments of the life cycle energy of buildings. Thus, there is a need to formulate system boundaries appropriately to include all the relevant components of building projects for a creditable life cycle energy assessment. Accurate assessment of the Life cycle energy of buildings will equip the stakeholders to take informed decisions on the adoption of appropriate design, construction and maintenance of buildings, which would result in the optimisation of energy requirements and improve the sustainability of the built environment. Additionally, the literature review indicated that very few of the previous studies focused on energy analyses of high-rise residential buildings which need higher research attention especially in the urban areas.

The general research question, as conceptualised earlier in Chapter 1, states: '*What opportunities exist for improvement in the energy performance of high-rise residential building projects during their life cycle?'*. Further, based on the research gaps identified above, the following specific research questions were formulated for further research inquiry in addition to the general research question (RQ):

RQ1 – What are the sub-systems that comprise a high-rise residential building project system from energy considerations?

RQ2 – How geographical representativeness influences the estimation of embodied energy of a high-rise residential building project?

RQ3 - What is the contribution of various life cycle stages in the life cycle energy footprint of a high-rise residential building project?

The identified RQs have been mapped to various objectives of the research work as shown in **Figure 2.10**.

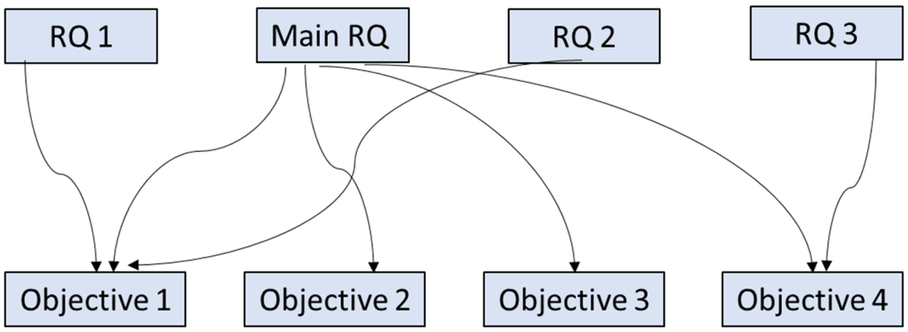


Figure 2.10 Mapping of research questions with objectives

2.7 RESEARCH AIM AND OBJECTIVES

The current study attempts to address the research gaps ascertained from the review of the literature. Therefore, based on the research questions, the aim of this research is to carry out the life cycle energy analysis of a high-rise residential building project. Also, as seen from the review of literature, the energy demand of a building project is made up of the energy requirement during various stages of a building project life cycle and thus involves a separate estimation of the energy footprint of each individual stage of a building project life cycle. Therefore, the four research objectives that emanate from this aim are as follows:

a) **Objective 1:** To estimate the embodied energy utilised by various components of a high-rise residential building project during the pre-occupation stage.
b) **Objective 2:** To study the energy demand of various components of a high-rise residential building project during the occupation stage.
c) **Objective 3:** To investigate the demolition energy consumption of various components of a high-rise residential building project during the post-occupation stage.
d) **Objective 4:** To analyse the overall energy requirements of a high-rise residential building project during its entire life cycle.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter discusses the research methodology adopted to answer the research questions. The study has adopted multiple research methods to answer the various research questions. The current investigation uses the case study research methodology as the dominant strategy to answer the research questions. Case study research methodology has been reported to be highly suitable in the project-driven construction industry and involving multiple business entities and organisations (Knight & Ruddock, 2009). Moreover, it captures the dynamics of the phenomenon being studied and provides a multi-dimensional view of the situation in a specific context (Järvensivu & Törnroos, 2010).

With respect to the design of the case study research methodology, one crucial question is to decide on the number of cases to be selected for the intended research. The selection of multiple case studies affords the benefits of comparing and contrasting the outcomes between similar cases, but it is resource-intensive. On the other hand, a single case study representative of typical occurrences is advantageous in the case of a longitudinal study of the same case along a longer time horizon (Yin, 2003).

The construction industry in India presently suffers from the absence of a policy driven system of data archiving and data sharing in respect of construction projects. Furthermore, the non-availability of data, the unwillingness to share data by the developers/consultants due to technical, commercial and legal sensitivity, and data collection challenges for multiple cases are major impediments to research work. Therefore, this study has adopted a single case-study approach to address the research problem. However, the limitations of selecting a single case study have been offset to some extent by the careful selection of a building project for conducting a longitudinal study. The selected case study building project typically represents the current trend in construction in organised residential developments in urban areas. Nevertheless, additional case studies would be desirable for validation, generalisation, and better reliability of the case study results.

For selecting an appropriate case study, initially, about thirty new residential projects located across India, at differing stages of completion, were shortlisted from websites of various builders/developers accessed through the internet. This was followed up with a telephonic discussion with the marketing teams and technical consultants to ascertain the composition of the project components, such as mechanical, electrical and plumbing (MEP) services and site development features apart from residential towers. Site visits were then undertaken to a few project sites to discuss the purpose of data collection and the extent to which data could be shared. There were general apprehensions about the sharing of data across all developers/technical consultants, citing commercial and legal concerns. Finally, after prolonged persuasion, data on one case study was obtained on conditions of extreme confidentiality.

3.2 ENERGY, BUILDINGS AND ENVIRONMENT

Energy is a universal physical quantity and may be defined as the capacity for doing work. It may exist in potential, kinetic, thermal, electrical, chemical, nuclear, or other forms. As per the first law of thermodynamics, energy can neither be created nor destroyed but only changes from one form to another (law of conservation of energy) (Britannica, 2022). In the International System of Units (SI), energy is measured in joules (NIST, 2022) and commonly measured in kilo Watt hours (kWh) in the case of electrical energy (U.S. Energy Information Administration, 2022).

Buildings consume large amounts of material and resources, causing environmental impact, which can be measured by environmental indicators such as energy, emissions, water, waste, land use, natural resources and indoor environmental quality. Among these indicators, energy and emissions have been found to be the most important by many authors (Alwaer & Clements-Croome, 2010; Maslesa et al., 2018; Toller et al., 2013). Energy is utilised during all stages of the building life cycle, from construction to operation of buildings and the end-of-life stage. Also, buildings gain or lose heat due to temperature difference between the internal and external surfaces of buildings by heat transfer through the building envelope fabric. In addition, buildings gain heat from the occupants' bodies and other activities such as cooking, lighting of luminaires, and operation of appliances by the occupants.

A considerable amount of energy is expended in buildings to maintain the thermal comfort of occupants. ANSI/ASHRAE Standard 55-2017 defines the thermal comfort conditions based on six factors, i.e., clothing insulation (clo), metabolic rate (Met), air temperature, average air speed, mean radiant temperature and relative humidity. For instance, for a clothing level of 0.65, metabolic rate of 1.3, average air speed of 1.0 m/s and relative humidity of 60%, the operative temperature range for thermal comfort has been specified between 22.3^{0}C to 26.5^{0}C. The average temperature of the human body is required to be maintained around 37^{0}C. Human bodies feel thermally comfortable if the rate of metabolic heat production is in equilibrium with the rate of heat loss to their surroundings (ASHRAE, 2017).

The energy thus consumed in the buildings is produced from a number of sources such as fossil fuels, hydropower, nuclear, and renewable sources (solar, wind, tidal, geothermal). However, in most countries, electricity is produced predominantly by the use of fossil fuels. For instance, fossil fuels had the largest share of approximately 80% of the global energy mix in 2019 (IEA, 2019), accounting for about 89% of the total global CO_2 emissions (Olivier & Peters, 2020). Thus, the production of energy being the single largest source responsible for greenhouse gas (GHG) emissions, energy consumption could be considered the most appropriate indicator to measure the environmental impact of buildings (Allacker, 2010; Junnila, 2006; Stephan & Stephan, 2014). Therefore, this study mainly deliberates on the energy analysis during various stages of a residential building project.

3.3 CASE STUDY DESCRIPTION

The case study project is a large modern housing complex comprising high-rise residential towers with heights up to 60 m, a basement for parking, and a total built-up area of about 160,000 m^2 located in the National Capital Region (NCR) of India. The apartments in the residential towers are fully air-conditioned except for the kitchen and the toilets. For the current study the buildings above 22.86 m height (i.e., above 7 storeys) from ground level have been considered as high-rise buildings based on the International Building Code (IBC) 2015 (International Code Council, 2015). The residential towers are reinforced cement concrete (RCC) frame structures with brick wall infills, wooden doors, UPVC frame windows with single glazing, and marble and ceramic tiles on floors. After a detailed study of contract documents, the following sub-systems have been identified based on functional criteria **(Table 3.1)**.

Table 3.1 Details of sub-systems and components

Sub-system category	Sub-system name	Components
Primary	Residential towers	Structure, internal plumbing, and internal electrification
Essential for functioning	External water supply	Water pumps, external plumbing, water tanks and water treatment plant (WTP)
	External electric supply	Electric transformers, external electric cables, stand-by generators and control panels
	Sewage treatment plant (STP)	STP structure, sewage treatment plant, sewage pumps and plumbing items.
	Vehicle parking	Structure (basements), internal lighting and area ventilation
	Site development features	Boundary wall, gate, internal roads, footpaths, external lighting, external drainage
	Heating ventilation and air conditioning (HVAC)	Air conditioners, refrigerant piping and power supply
Mandatory by regulations (Ministry of Urban Development, 2016)	Elevators	Lift well, lift lobby and elevators
	Firefighting	Fire tanks, pumps, fire hydrants/ plumbing items, fire detection and firefighting equipment
Optional & recreational	Sports facilities	Swimming pool, tennis court and gym equipment
	Site beautification features	Landscaping, water bodies

3.4 SYSTEMS APPROACH

A system may be defined as “a set of components designed to achieve a set of goals”. Similarly, the systems approach is a holistic approach to problem solving and has the following attributes: a) system components, their activities/interactions with other sub-systems, and goals; b) input resources to the system; c) internal and external environment of the system; d) objectives of the system as a whole; e) management of the system to achieve its objectives; and f) output of the system (Churchman, 1968; Jenkins, 1969). In this study, the overall objective of the ‘Building Project System’ is to provide a comfortable place of living to its occupants. This system objective is accomplished through each sub-system meeting its assigned goals. For example, the external electric supply sub-system ensures the availability of reliable and quality power supply to the occupants. Similarly, the water supply sub-system meets its goals by providing water for various activities of occupants in their apartments (drinking, cooking, bathing, washing, cleaning, flushing), landscaping, requirements of the swimming pools and other sports and common areas. Thus, each sub-system interacts with one or more sub-systems to perform their designated functions.

Further, the inputs to the system are materials, energy (direct and indirect), and water that are used during all life cycle stages of the building project. Indirect energy includes the use of resources such as transport, plant and machinery, human resource and finances. Similarly, the outputs of the system are carbon emissions, water, and waste material produced during various stages of the building project life cycle. For the purpose of this study, the outputs of carbon emissions, water, and waste material (finally disposed of in landfills) have been excluded from the system boundary and are considered beyond the scope of this study.

The system boundary model shows the project components (sub-systems) of the Building Project System (hereafter referred to as 'system') (**Figure 3.1**) and the stages of the building life cycle (**Figure 3.2**) included in the scope of this study. It also shows the interaction among the various sub-systems. It is assumed that the 'Internal Environment' within the system is controllable by the project developers and their team. The developer has the authority to select the various elements such as project design, specifications, building material, employment of manpower, tools, plant and machinery for completion of the project. On the other hand, the infrastructure available in the 'External Environment' is uncontrollable by the developer and the developer is constrained to utilise the infrastructure as available, as it falls within the purview of the state agencies.

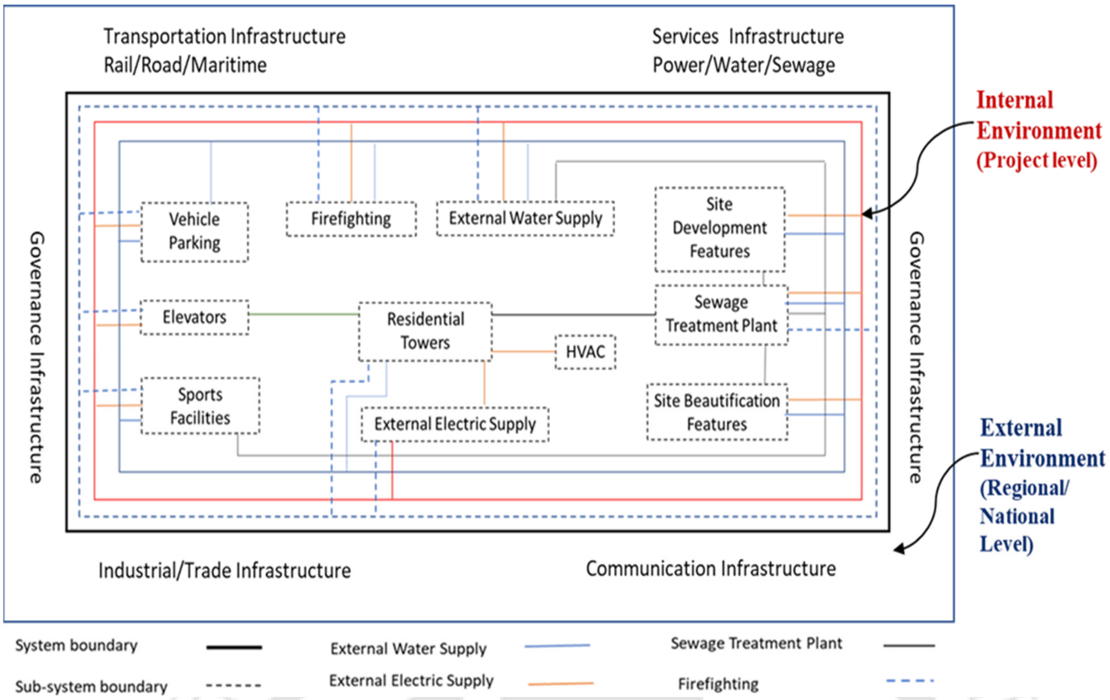


Figure 3.1 Components of the building project considered

PRE-OCCUPATION STAGE						**OCCUPATION STAGE**							**POST-OCCUPATION STAGE**			
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
√	√	√	√	√	√	√	√	√	√	√	√	X	√	√	√	√
Pre-design / design phase	Raw material extraction	Transport	Manufacturing	Transport to site	Assembly/construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal

√ - Stage included, X – Stage Excluded

Figure 3.2 Stages of building project life cycle considered (Adapted from ISO (2022))

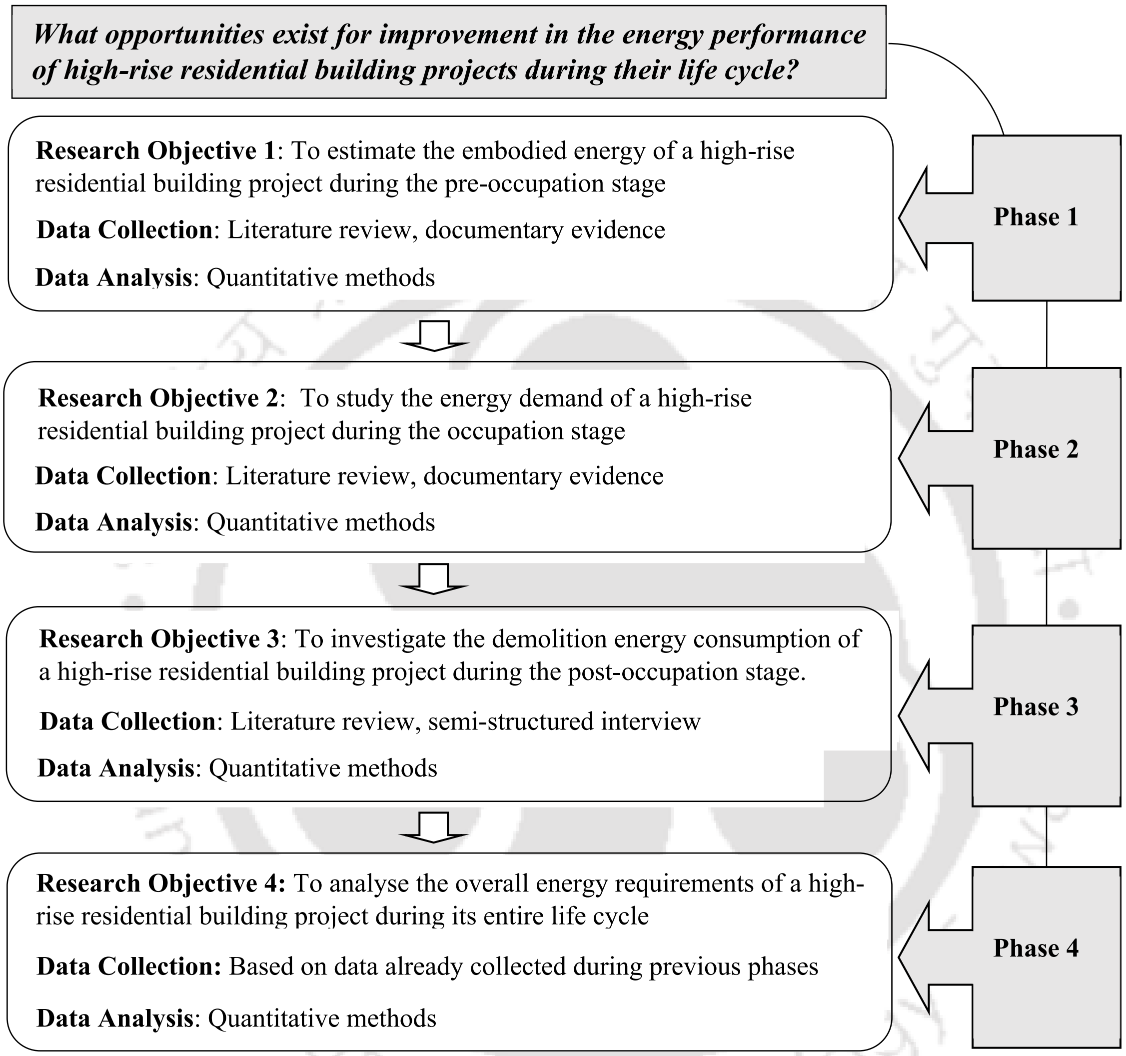
The supply chain process of materials and services during different stages of a building life cycle may be of '*pull type*' or '*push type*' based on demand and supply requirements (Lin et al., 2022). In this system, during the construction phase, the supply chain process used is pull type, as building materials, tools and plants are procured from time to time based on the quantum of work, time required for procurement, availability of storage space and rate of consumption. Whereas, during the building operation phase, a combination of pull and push processes is employed to meet the occupant demand, wherein services such as power supply are always made available in anticipation of occupant demand (push type), but other services such as water supply and sewage treatment are provided based on actual consumption of water/generation of sewage (pull type). Similarly, during the end-of-life phase of the building, the demolition activity is a pull-type process where manpower and machinery are employed on as requirement basis. At the same time, the disposal of waste to a processing/recycling plant and landfill site is a push-type process since site clearance is a natural follow-up after building demolition. Appropriate supply chain design and management can improve the energy consumption of supply chain processes (Marchi & Zanoni, 2017).

The scope of this study has certain exclusions. The cost of land procurement has been excluded as land is not an expendable item and would remain available for future use even after the end-of-life stage of the building project. The cost or energy consumed on renovations over and above the requirement of regular repair/maintenance/replacements, interior finish such as wardrobes and kitchen cabinets, furniture and appliances, and cooking, have been excluded as these are difficult to quantify, being dependent on personal choices of the occupants. Similarly, the cost/energy incurred on property registration and property tax and the profits earned by the developer on real estate transactions have also been excluded from the scope of this study.

3.5 RESEARCH DESIGN

The research design adopted for the present study is presented in **Figure 3.3.** The study has adopted a four-phase research inquiry to achieve the objectives described in the subsequent sections. The evidence in the case study method of research could consist of physical artefacts, documents, archival records, direct observation, participant observation, and interviews. This study resorted to the collection of data from multiple sources of evidence to afford convergence of data points, leading to the triangulation of mixed method research (Yin, 2009).

The primary data was collected from multiple sources of evidence, i.e., developer, consultants, project manager, contractors and suppliers. Apart from this, physical visits were also undertaken to the project site, which provided an opportunity to verify the documentary evidence through direct observation and informal discussion with the personnel working at the operational level. This helped in the triangulation of information received from primary and secondary data sources as recommended by (Yin, 2009).



What opportunities exist for improvement in the energy performance of high-rise residential building projects during their life cycle?

Research Objective 1: To estimate the embodied energy of a high-rise residential building project during the pre-occupation stage

Data Collection: Literature review, documentary evidence

Data Analysis: Quantitative methods

Research Objective 2: To study the energy demand of a high-rise residential building project during the occupation stage

Data Collection: Literature review, documentary evidence

Data Analysis: Quantitative methods

Research Objective 3: To investigate the demolition energy consumption of a high-rise residential building project during the post-occupation stage.

Data Collection: Literature review, semi-structured interview

Data Analysis: Quantitative methods

Research Objective 4: To analyse the overall energy requirements of a high-rise residential building project during its entire life cycle

Data Collection: Based on data already collected during previous phases

Data Analysis: Quantitative methods

Figure 3.3 Research methodology adopted for the current study

3.5.1 Phase 1

Data collection

The research objective of Phase 1 is ***'to estimate the embodied energy of a high-rise residential building project during the pre-occupation stage'***. To meet this research objective, the study has adopted quantitative research techniques. During this phase, energy is consumed on all activities such as extraction and processing of raw material, production of building material and its transportation, and on-site construction of building projects. Data was collected in terms of contract documents, drawings and purchase orders. Shortfalls in data were made up through subsequent data collections as and when required during the progress of the research. Documentary evidence was verified through actual site visits, viz., direct observation and discussion with site engineers and project management.

Data analysis

The embodied energy consumed during the pre-occupation stage of the buildings is known as initial embodied energy (IEE). The IEE of sub-systems has been estimated based on input-output based hybrid analysis method (Langston et al., 2018; Zhang & Wang, 2016). The steps followed for the estimation of IEE are:

a) estimation/extraction of Bill of Quantities (BOQ) (Shao et al., 2014) of composite items of work in each sub-system.
b) calculation of quantities of those main materials from the composite items of work for which we want to compute the IEE, e.g., quantities of bricks and cement used in brickwork.
c) finding the energy coefficient of the material from the literature, if available.
d) developing energy coefficient of those materials or items of work whose details are not available in the literature based on Input-Output (I-O) Table 2013-14 of the Indian economy from (Singh & Saluja, 2018).
e) computing the IEE of the sub-system using the input-output hybrid analysis method (Crawford, 2011; Zhang & Wang, 2016).

3.5.2 Phase 2

Data collection

The research objective of Phase 2 is **'*to study the energy demand of a high-rise residential building project during the occupation stage*'**. The research strategy adopted in the second phase is case study, as mentioned earlier. During this phase, direct and indirect energy is consumed on lighting, operation of services, repair/maintenance/replacements, and management of facilities. Therefore, data collection was carried out on a) power consumption on lighting and operation of services from the energy meter records of the facility manager; b) cost of housekeeping and repair/maintenance of common area and facilities, including the cost of annual maintenance contracts and building insurance; c) cost of administrative and technical manpower employed for operation, maintenance and security of the building project. Verification of data was accomplished by actual site visits of relevant services and technical discussion with the facility manager and administrative and technical supervisors to crosscheck the type and number of equipment, their power ratings, average hours of operation per day and deployment of manpower.

Data analysis

Data analysis was carried out by quantitative analysis using simple arithmetic to estimate the direct and indirect energy consumption during the occupation stage of the building project. Steps followed for estimation of energy consumption during the Occupation Phase are:

a) ascertaining service life of components from literature such as past studies, maintenance manuals, original equipment manufacturer's (OEM's) specifications and environment product declarations (EPDs).
b) estimating the replacement cost of components in each sub-system based on the number of replacements required during the building life span, which has been assumed as 50 years for this study.
c) computing embodied energy consumption due to replacements based on input-output based hybrid analysis and input-output analysis (Crawford & Treloar, 2003; Lenzen, 2000).
d) ascertaining the cost of repair and maintenance of sub-systems based on industry benchmarks or annual maintenance contracts (AMCs).
e) computing embodied energy expended on repair/maintenance/replacements based on sectoral energy intensity as estimated from input-output tables (Crawford & Treloar, 2005).
f) computing OE consumed for the operation of sub-systems in terms of power consumption, cost of manpower deployed for operation and cost of management.

3.5.3 Phase 3

Data collection

The third phase of the research inquiry addresses the third research objective: '***To investigate the demolition energy consumption of a high-rise residential building project during the post-occupation stage.*** The case study has been the research strategy adopted for this phase. In this phase, direct and indirect energy is consumed for demolition of the sub-systems, transportation of demolition waste to reuse/recycling/processing plants and landfill sites, processing of demolition waste, and administration of the demolition process. The project selected for this case study has been a newly constructed building in 2019 and is being considered for prospective demolition after a life span of 50 years. Therefore, data was collected on the method and cost of demolition incurred on the actual demolition of similar buildings using controlled explosion (representative case study). Data was collected through semi-structured interviews with technical consultant, project manager and site engineer of the demolition project of the representative case study. Cost elements considered for cost estimation of controlled explosion are shown in **Table 3.2**.

In addition, data was collected from service engineers, senior practising engineers and OEMs on the quantity of scrap material that could be recovered from electro-mechanical equipment used in the sub-systems (such as elevators, transformers, diesel generator sets, firefighting equipment) during disposal at the end-of-life stage of the building project. The data on the cost of scrap material recovered from demolition waste was collected from scrap vendors duly corroborated by the demolition contractor and technical consultant **(Table 3.3).**

Data analysis

The building project is considered to be demolished using a hybrid method comprising deconstruction, controlled explosion, and mechanical demolition. Initially, the likely amount of demolition waste generation was estimated using the lifetime analysis method by utilising material flow analysis during construction stage with modifications (Poon, 1997). Material flow during repair, maintenance and replacements was excluded from the scope of the study as the cost of dismantling and removal of old items is invariably adjusted in the cost of repair/replacement work as per existing practice in the Indian construction industry.

Table 3.2 Cost elements considered for cost estimation of the controlled explosion

Type of cost	**Cost elements considered**
Administrative cost	Cost of clearances from Government agencies, including licences for explosive transport and usage
	Cost of technical consultant to assess the structural safety of building under demolition during preparatory work for controlled explosion
	Cost of pre and post explosion structural audit of neighbouring properties, monitoring of essential parameters related to actual controlled explosion (e.g., ground vibration, air overpressure, noise level)
	Cost of site safety measures- CCTV cameras, curtain wall
	Cost of office establishment-project office and office staff
	Cost of third-party insurance against damage/injury to personnel and properties during demolition work
	Management cost- chief executive officer, project manager, project coordinator
Cost of plant and machinery	Diamond core cutting machine for drilling of boreholes for explosive placement
	Lift and hoist for labour and material
	Operation of DG Sets-fuel cost, capital cost
	Cost of dust control system during preparation of building for explosion and actual explosion
Labour and technical supervision cost	Plant and machinery operators, skilled and unskilled labour, security staff and site engineers
Cost of explosive related work	Cost of explosive consultant for design and execution of controlled explosion (supervision, charging, and firing of explosives)
	Cost of explosives and explosive accessory
Cost of expendables	Chain link fence and geotextile fabric for wrapping of blast columns, personal protective equipment- safety gear, safety shoes and helmets
Contractor's profit	The contractor's profit was considered as 10 percent based on discussion with the demolition contractor

The average wastage rate of 10% for building materials during the onsite construction considered by Treloar (1998), Shen et al. (2005) and (Hao et al., 2008) was modified to 5% for the current study to cater for improvement in construction methods.

Table 3.3 Details of data collection for quantity and cost of scrap material

Type of data	Source of data	Form of data collected	Method of data collection
Quantity of scrap material that could be recovered from electro-mechanical equipment	Service engineers-3 Senior practicing engineers-6 Demolition contractors-4 OEMs-3	Scrap material estimates, OEM specifications	Semi-structured interview, personal communication, technical specifications
Cost of scrap material recovered from demolition waste	Scrap vendors-4 Demolition contractors-4 Technical consultant-2 Web sites- https://www.indiamart.com/, https://www recycleinme.com/	Prevailing scrap rate estimates	Semi-structured interview, internet search

OEM- Original equipment manufacturer

In addition, wastage can also occur due to rework for non-conformance in design or execution, and change orders by the client. However, the actual costs of rework are often difficult to quantify due to the absence of a formal data capture mechanism in the construction agencies (Matthews et al., 2022). Moreover, rework may not be necessary for all projects (Love & Matthews, 2020). In any case, since rework remains an unplanned activity in most construction agencies, the cost of rework is usually offset from their profits (Love et al., 2022). Therefore, the quantity of waste material due to rework during onsite construction has not been considered while estimating the quantity of waste generated at the post-occupation stage from the bill of quantities extracted from the contract documents. Additionally, the wastage rate of 5% for building materials during the construction stage considered in this study is also in line with some of the past studies, such as that by (Hoxha et al., 2016).

Furthermore, the recovery rate (sort level) for all reusable or recyclable materials was assumed as 95% based on Thormark (2002) and the balance of 5% of all materials was assumed to form part of mixed debris consigned to landfill.

The demolition energy required for the demolition of the building project was estimated broadly in two steps given below. The detailed methodology has been elucidated in Chapter 6:

(i) Estimation of the net cost of demolition incurred for demolition, transportation, waste processing and cost recovered on recycling of scrap.
(ii) Estimation of demolition energy expended based on input-output analysis

In step 1, the net cost of demolition incurred for each sub-system has been computed based on Equation (Eq) (3.1).

$$C_{net} = \sum_{i=1}^{n} C_{net(i)} = \sum_{i=1}^{n} [\, C_{scrap(i)} - C_{dem(i)} - C_{trans(i)} + C_{proc(i)} \,] \qquad \ldots (3.1)$$

Where $C_{net(i)}$, $C_{scrap(i)}$, $C_{dem(i)}$, $C_{trans(i)}$, and $C_{proc(i)}$ denote the et cost of demolition, cost recovered from the sale of scrap, cost of demolition activity, cost of transport for reuse/recycle/landfill and cost of processing demolition waste for each sub-system 'i' respectively. Whereas C_{net} denotes the overall cost incurred during the whole building project demolition.

In step 2, the demolition energy incurred during the demolition of each sub-system was computed using Eq (3.2):

$$DE = \sum_{i=1}^{n} DE_{(i)} = \sum_{i=1}^{n} [\, C_{net(i)} \text{ X } EI_{constr} \,] \qquad \ldots (3.2)$$

Where:

$DE_{(i)}$ and $C_{net(i)}$ are demolition energy and net cost of demolition of each sub-system, respectively, EIconstr is the energy intensity of the construction sector, and DE is the demolition energy requirement of the whole building project. EIconstr has already been calculated during energy estimation at the pre-occupation stage as 37.26 GJ/Rs Lakhs of the output of the construction sector, using the input-output analysis method (Jiang et al., 2019; Onat et al., 2014b).

3.5.4 Phase 4

Data collection

Phase 4 of the research investigation is focused on meeting the fourth research objective: ***To analyse the overall energy requirements of a high-rise residential building project during its entire life cycle.*** Life cycle energy is the sum total of energy incurred during all stages of the life cycle. of a building project from the pre-occupation stage to the post-occupation stage. The results of this phase are based on an analysis of the findings of previous phases. Thus, no primary data is required to be collected during this phase.

Data analysis

The life cycle energy of a building project can be expressed as:

$$LCE = IEE + (REE + OE) + DE \qquad \text{...Eq (3.3)}$$

Where IEE, REE, OE. DE and LCE represent the initial embodied energy, recurring embodied energy, operating energy, demolition energy and life cycle energy, respectively. In this phase, the results are computed based on literature survey and results obtained from previous phases of this study. In addition, sensitivity analysis was carried out to examine the effect of variation of operational energy demand and building life span on the relative proportion of embodied energy and operation energy with respect to life cycle energy.

CHAPTER 4: ENERGY ANALYSIS OF PRE-OCCUPATION STAGE

4.1 INTRODUCTION

The pre-occupation stage of a building project comprises a large number of activities starting from project conception to the completion of construction, including installation of connected equipment. The completion of the pre-occupation stage indicates that the building is complete in all respects and is ready for use to perform its intended functions. It also marks the beginning of the next stage of a building life cycle, the occupation stage. Similarly, the occupation stage culminates into the post-occupation or demolition stage at the end of the building life span.

Embodied energy (EE) of a building is the cumulative energy consumed during pre-occupation stage from extraction of raw material to actual construction (Initial EE), the energy required during operation stage (occupation stage) in repair, maintenance, refurbishment (Recurring EE) (Fay et al., 2000; Treloar et al., 2001a; Troy et al., 2003), and the demolition energy (DE) (Ding, 2004) expended during the post-occupation stage. However, this chapter mainly focuses on estimating the Initial EE incurred during the pre-occupation stage of a building project.

Embodied energy quantification is more complex and resource intensive as compared to operational energy owing to a large number of building materials and electro-mechanical equipment used/installed during construction and non-availability of region-specific inventory databases.

As observed during the systematic review of literature, a large number of studies have not considered all sub-stages of various life cycle stages of buildings. For instance, the pre-design, design, and construction sub-stages (Esteghamati et al., 2022) during the pre-occupation stage have been generally ignored despite energy consumption on various activities, as shown in **Figure 4.1.** On the other hand, most of the studies have excluded the mechanical, electrical and plumbing (MEP) services (Basbagill et al., 2013; Rodriguez et al., 2020) and site features (Dixit, 2019) from the scope of the study, thus leading to underestimation of the embodied energy burden of the building projects.

Figure 4.1 Activities during the pre-occupation stage

This chapter is intended to address the research gaps as identified from the review of the literature. Thus, the aim of this chapter is *to carry out the energy analysis of a high-rise residential building project during the pre-occupation stage of its life cycle*. The scope of the study includes all components of the building project, such as residential towers, MEP services and site features. Data for this phase of the study was collected in the form of documentary evidence, such as contract documents, building drawings, and purchase orders. The energy analysis was carried out using the input-output hybrid analysis method on the input-output tables of the Indian economy sectors. The succeeding sections describe the material and methods, results, and discussion, followed by a summary of the chapter.

4.2 MATERIAL AND METHODS

4.2.1 Methodology used for the estimation of embodied energy

Among the methods used for EE analysis in past studies, though inventory analysis is highly resource intensive (Suh & Huppes, 2002), it remains the primary method of EE analysis wherein process analysis, input/output (I-O) analysis and hybrid analysis methods have been widely used (Cellura et al., 2013; Maierhofer et al., 2022; Zhang & Wang, 2016).

Process-based embodied energy (EE) is considered to be more accurate and reliable; however, this assessment approach is reported to be impracticable and incomplete due to truncation of system boundaries and exclusion of many upstream processes, such as capital energy inputs into plants and machinery used in the building material production (Pullen, 2000b; Stephan et al., 2019). On the other hand, the input/output-based analysis makes use of economic data of money flow among various sectors of the industry derived from the input/output tables published by the national governments. Thereafter, the economic flows are converted into energy flows by applying average energy tariffs on the cost of the products (Lenzen, 2002). The input-output method has the advantage of encompassing complete system boundaries and affording geographical representativeness (Dixit et al., 2012). But this method also needs to improve on problems such as the assumption of homogeneity and proportionality, errors and uncertainty of economic data (for example, energy tariff and product cost), and aggregation and grouping of sectors (Crawford & Treloar, 2005).

The hybrid method, which combines the assessment approaches of the earlier two methods, starts with a process analysis of readily available energy input data of the final production stage and one more stage in the upstream. It then substitutes the process analysis method with the input/output method when it is difficult to obtain reliable and consistent information regarding complex upstream processes (Lenzen, 2000). Amongst the hybrid methods, the input-output based hybrid analysis method is preferred over the process-based hybrid analysis method as it includes most of the direct and indirect energy inputs during the process of building material production. It also encompasses the entire system boundary and is considered comprehensive and complete vis-à-vis the three inventory analysis methods discussed above (Chang et al., 2014; Lenzen & Treloar, 2004). However, Dixit (2017b) further argued that the input-output based hybrid method also suffers from discrepancies of "completeness, accuracy and specificity" and proposed its refinement through the use of primary energy factors, the inclusion of human and capital energy, and material specific disaggregation of the industry sectors.

Embodied energy results could vary due to differences in 'data quality parameters' used by different studies. Some data quality parameters include the type of data used (primary or secondary), geographic location of data used compared to that of study buildings, data vintage, and incompleteness of data (Dixit et al., 2010). As discussed in Chapter 2: Review of Literature, out of these parameters, the geographic representativeness of data is one of the most important parameters that could influence the results of the EE analysis of a building. To elucidate further, the EE coefficients used by some international and frequently referred Indian studies are shown at **Table 4.1.** A large variation is visible between embodied energy coefficients used by the international and Indian studies. In addition, large variation is also observed amongst EE coefficients used by various Indian studies mainly due to differences in data vintage, type of method used for estimation of EE coefficients, and system boundary selection.

Table 4.1 Variation in embodied energy coefficients due to geographic origin

		EE Coefficients (GJ/Unit)							
Main Material	Unit	Crawford (2011)	Dixit (2017a)	Debnath et al. (1995)	Reddy and Jagadish (2003)	Shukla et al. (2009)	Maini and Thautam (2009)	Praseeda et al. (2015)	IFC (2017)
Data origin and method of computation		Australian (IOBH)	United States (IOBH)	Indian (IO)	Indian (PEB)	Source/ method not declared	Indian (secondary sources)	Indian (PEB + TE)	Indian (IOBH)
Steel	ton	85.46	79.55	20.62	42.00	54.00	33.33	34.23	38.00
Cement	ton	16.96	19.72	9.29	5.85	7.79	4.60	3.62	6.40
Cement concrete	m^3	6.75	2.78				2.06		2.09
Bricks	m^2	0.56	1.04	0.31	0.25	0.35	0.22	0.51	0.22
Stone marble, granite	ton	0.09	2.84					0.82	
PVC	ton	156.90	109.00			104.15	115.00		55.00
Plywood	m^3	30.35	32.70						10.80
Plasterboard / Gypboard	ton	11.80	23.54						6.80
Aluminium	ton	252.60	184.45		236.80		260.00	150.69	310.00
Glass float	ton	173.00	138.61	36.00	25.80			8.94	17.00
Ceramic tiles	ton	12.63	58.82				2.50	18.00	8.20
Paint	ton	236.84	107.11	93.75		144.00			
Gravel /Aggregate	ton	0.36	2.84	1.14	0.01		0.22		0.11
Bitumen	ton	46.53		2.98					
Copper	ton	378.90	57.38			110.20	112.00		90.00

IO- Input output analysis, IOBH- Input output based hybrid analysis, PEB- Process energy based analysis, TE- Transportation energy, EE- Embodied energy, GJ-Giga Joules, IFC- International Finance Corporation

Based on the review of available methods above, the IEE of sub-systems has been estimated using the input-output hybrid analysis method, as it combines the advantages of both methods (process analysis and input-output analysis) while minimising their shortcomings (Crawford, 2011; Stephan & Stephan, 2014; Zhang & Wang, 2016). The steps followed for the estimation of EE are as follows: -

a) Collection of data and estimation/extraction of Bill of Quantities (BOQ) of composite items of all works executed in a sub-system, e.g., the quantity of brickwork or plaster used in the construction of that sub-system.

b) Calculation of quantities of those main materials from the composite items of work for which IEE is to be computed, e.g., quantities of bricks and cement used in brickwork or quantity of cement used in plasterwork (cement mortar).
c) Finding the EE coefficient of the material from published material.
d) Developing EE coefficient of those materials or items of work whose details are not available in the public domain.
e) Estimating energy intensity of the construction sector.
f) Computing IEE of the sub-systems using Eq (4.1) below.

Detailed methodology of IEE estimation is given in subsequent paragraphs.

4.2.2 System boundary selection and data collection

The system boundary selected for the energy analysis during the pre-occupation phase of this case study building project includes the sub-stages A0 to A5 of the building project life cycle. Namely, the pre-design / design phase (A0), raw material extraction (A1), transport (A2), manufacturing (A3), transport to site (A4), assembly/construction (A5) sub-stages have been considered in the system boundary. Similarly, all sub-systems of the case study building project were also included in the system boundary for estimating the IEE during the pre-occupation stage. Data related to project construction was collected in terms of contract documents, drawings and purchase orders through documentary evidence. In addition, data on EE coefficients of building material was collected from literature to the extent available, and the EE coefficients of the balance material and equipment were computed from the Input-Output Table of Indian economic sectors. Data was collected from multiple sources of evidence, i.e., developer, contractors, suppliers, consultants, project managers, senior engineers, and literature. Verification of documentary evidence was carried out through actual site visits, viz., direct observation and technical discussion with senior site engineers and project management. This helped in the triangulation of information received from primary and secondary data sources, as recommended by Yin (2009).

4.2.3 Estimation of bill of quantities

Accurate calculation of material quantities and their cost is the crucial and most tedious part of this research, as these parameters can greatly influence the embodied energy results. Considering the vast number of materials used for modern building construction, it would neither be desirable nor productive to find the process energy of each material. Therefore, only those materials were selected for further analysis whose process energy intensity was high or when they have been used in comparatively higher quantities. The selection of these materials is dependent on the composition of each sub-system. For example, in the case of structural materials, concrete, steel, cement, bricks, timber, glass, and paint would be important.

Details of material quantities and construction costs were extracted/worked out from contract documents, building drawings, purchase orders, rate analysis of contractors and Central Public Works Department (CPWD, 2013), Ministry of Road Transport and Highways Specifications (MoRTH, 2013), technical specifications of original equipment manufacturers (OEMs) and Indian Standard Codes of practice such as BIS (2000). Some sources of data used for material specifications are shown in **Table 4.2** purely as an illustration. The extracted data on each sub-system was organised into 3-tier hierarchical levels viz., Element Group, Element and Material. Sub-system-wise details of material, EE coefficients and unique sectoral energy of the material production process are shown in **Tables B-1** to **Table B-11** of **Appendix B.**

Table 4.2 Sources of data for material specifications (Illustrative)

Item/ Material	**Source for specification**	**Ref**
MS Pipes	IS 1239-1 (2004): Steel Tubes, Tubulars and Other Wrought Steel Fittings, Part 1: Steel Tubes [MTD 19: Steel Tubes, Pipes and Fittings]	BIS (2004)
Electrical conduits	IS 9537-3 (1983): Conduits for electrical installations, Part 3: Rigid plain conduits of insulating materials (Superseding IS:2509) [ETD 14: Electrical Wiring Accessories]	BIS (1983)
UPVC Pipes	IS 4985 (2000): Unplasticized PVC Pipes for Potable Water Supplies - [CED 50: Plastic Piping System]	BIS (2000)
Cement constants	Central Public Works Department, Delhi Schedule of Rates-2013, Director General, CPWD, Nirman Bhawan, New Delhi, 2013.	CPWD (2013)
Coarse Aggregate	Specifications for road and bridge works, in Indian Roads Congress, Ministry of Road Transport & Highway, New Delhi, India.	MoRTH (2013)

4.2.4 Estimation of embodied energy of sub-systems

Based on the strengths and weaknesses of available methods, as discussed above, the input-output based hybrid method was selected for computing the initial embodied energy (IEE) of the case study building project. The IEE of sub-systems was estimated based on Equation (Eq) (4.1) (Crawford, 2011).

$$IEE_b = \sum_{m=1}^{M} (Q_m \times EC_m) + [TER_n - \sum_{m=1}^{M} TER_m] \, X \, C_b \qquad \ldots (4.1)$$

Where, IEE_b = Initial embodied energy of the building project sub-system in Giga Joules (GJ)

Q_m = Quantity of each material consumed

EC_m = Embodied energy coefficient of material m

TER_n = Total energy requirement of construction sector per Rs Lakhs

TER_m= Unique sectoral energy requirement of material production for which process data is available per Rs Lakhs

C_b = Cost of building project sub-system in Rs Lakhs

Equation 4.1 can be rewritten in simple terms as follows:

IEE_b = Total material process energy + Remainder energy of the sub-system.

In equation 4.1 above, the total material process energy covers the IEE consumed during the manufacturing sub-stage (A3) of all materials used in the construction during the pre-occupation stage of the building project sub-system under consideration. On the other hand, the remainder energy of the sub-systems includes IEE incurred on all upstream activities during the balance sub-stages i.e., the pre-design / design (A0) raw material extraction (A1), transportation of raw material from material extraction site to manufacturing site (A2), transport from manufacturing site to building construction site (A4), and assembly/installation/ construction of material during actual on-site construction (A5). The cost of building project sub-system (C_b) includes the cost of pre-design and design phase activities, cost of building material at the construction site and the cost incurred in the assembly/erection/ installation of this building material during the actual construction.

4.2.5 Estimation of energy intensity of construction sector and other sectors using Input-Output Tables

The energy intensity of the construction sector has been estimated using the Input-Output (I-O) Table 2013-14 for the Indian Economy from Singh and Saluja (2018), as most of the contracts for this building project were finalised during 2013-14. This ensured that the error in the estimation of EE due to the use of old vintage data was eliminated in this study. The 130 x 130 commodity x commodity matrix table was selected because it has been reported to be more suitable than the industry x industry matrix table in most applications since demand is for a particular commodity or group of commodities and not for the mixed range of output of an industry (Ministry of Statistics & Programme Implementation [MoSPI], 2012). The commodity x commodity matrix includes five fuels relevant to energy input to all sectors: coal and lignite, crude petroleum, natural gas, petroleum products, and electricity. Out of these fuels, most of the crude petroleum and natural gas goes into the production of petroleum products; hence, these two sectors have been neglected. The fuel inputs to sectors were converted from monetary units to energy units based on their price in 2015-16 (Coal India, 2013; Economics and statistics Division, 2016) and deflated to 2013-14 using the Wholesale Price Index and energy conversion factors. Since coal and lignite are also used as fuel input for the production of electricity, the direct input of coal to electricity was set to zero to avoid double counting. The energy intensity of various sectors of the Indian economy has been estimated using equations 4.2 and 4.3 as per the details given below:

The basic balance equation for the input-output table based on Leontief (1986) in matrix form is given by Eq (4.2):

$$X = (I - A)^{-1}F \tag{4.2}$$

Where:

X is a n x 1 matrix (n=130) with elements X_i representing gross output of sector i,

A is a n x n matrix with elements $a_{ij} = \left(\frac{x_{ij}}{x_j}\right)$ representing the input of ith sector to jth sector per unit of the jth sector

F is n x 1 final demand matrix, with each element F_i representing the final demand for the sector i's products.

Similarly, the basic balance equation for the energy input-output table in matrix form is given by Eq (4.3) (Tiwari, 2000) :

$$N = EX + \bar{N} \tag{4.3}$$

Where:

N is a 3 x 1 matrix with elements N_k representing the total energy use by fuel type k,

X is as defined above.

E is a 3 x n matrix with elements e_{kj} representing direct energy input of fuel k into sector j.

$\bar{N}$ is a 3 x 1 matrix with elements N_{kf} representing the total energy use by fuel type k to meet the final demand of fuel sector k.

Substituting the value of X from eq (4.2) into Eq (4.3), we get Eq (4.4)

$$N = E(I - A)^{-1}F + \bar{N} \tag{4.4}$$

Eq (4) can be re-written as Eq (4.5)

$$N = GF + \bar{N} \tag{4.5}$$

The rows of the G matrix give each sector's total direct plus indirect energy intensity by fuel type.

Details of the total energy requirement of material production process (TERm) for material used in the construction sector, as computed from Input- Output Table 2013 using Eq (4.5) are shown in **Table 4.3**. The total (direct and indirect) energy intensity of the construction sector (TERn) from the G matrix, as computed, works out to 37.2639 GJ/ Rs Lakhs of the output of the construction sector.

Table 4.3 Total energy requirement (TERm) for production processes of material used in the construction sector

Input-Output Sector	**Material**	**Elements**	**TERm (GJ/Rs Lakhs)**
Iron and steel foundries	Steel	Reinforcement bars	17.2619114
Cement	Cement	Plastering, cement mortar	7.1108905
Other non-metallic mineral products	Concrete, glass, structural stone	Structural components, floor, doors, windows	0.8164207
Structural clay products	Clay bricks, tiles	Walls, floor, etc	0.5596949
Plastic products	PVC, UPVC	Window frames, pipes, PVC conduits	0.2801441
Paints, varnishes and lacquers	Paints, varnishes and lacquers	Painted surfaces, walls, MS structural items, doors, etc	0.2259275
Electrical wires & cables	Metals, insulating materials	Electrical wires and cables	0.1404495
Miscellaneous manufacturing	Various materials	Sports and athletic goods	0.0993293
Water supply	Water supply items	Water treatment plant, water distribution system	0.0248982
Wood and wood products	Timber, processed wood	Doors, laminated flooring	0.0087736
Electronic equipment	Access control hardware and software	Vehicle tag scanner, CCTV camera, etc.	0.0017583
Other non-electrical machinery	Fabricated metal work	Elevators, firefighting equipment and appliances, air conditioners	0.0013789
Communication equipment	Various materials	Intercom equipment, telephone handsets	0.0000020
Other sectors with smaller share grouped together	Various materials	Miscellaneous items	10.7323974
Construction sector total energy intensity (TERn)			37.26397648

4.2.6 Developing India specific EE coefficients from Input-Output Tables

India specific EE coefficients of a number of construction materials/equipment were not available in the literature, as also observed by The Energy and Resources Institute (TERI), 2012. Therefore, EE coefficients of material/equipment not available in the literature were computed using Eq (4.5) above and Input-Output Tables 2013-14 of the Indian Economy given in Singh and Saluja (2018). Detailed methodology for the computation of EE coefficients has already been covered in Section 4.2.5 above. The construction material/equipment, along with their corresponding India specific EE coefficients as computed in this study, is shown in **Table 4.4.**

Table 4.4 Embodied energy coefficients estimated from Indian economy sectors

Construction material/ equipment	**EE coefficients India (GJ/Rs Lakhs)**	**Input-output sector of Indian economy** (Sector code & name)
Pumps- water supply	96.75	87-Other non-electrical machinery
Water treatment plant (WTP)	19.90	108-Water supply
Transformers, HT/ LT Panels, DG Sets	52.68	88-Electrical industrial machinery
Feeders, HT/LT cables	56.47	89-Electrical wires & cables
Sewage treatment plant	26.76	129-Other services
Stoneware glazed Pipe	42.99	76-Other non-metallic mineral products
Light fixtures	41.90	91-Electrical appliances
Electrical wiring internal	56.47	89-Electrical wires & cables
Fire pumps, hand appliances for firefighting	96.75	87-Other non-electrical machinery
Fire detection system	26.15	94-Electronic equipment
Access control hardware and software	26.15	94-Electronic equipment
Intercom equipment	23.61	92-Communication equipment
UPS	60.53	93-Other electrical machinery
Split air conditioners	96.75	87-Other non-electrical machinery
Electrical accessories	60.53	93-Other electrical machinery
Elevators	96.75	87-Other non-electrical machinery
Recirculation pumps	96.75	87-Other non-electrical machinery
Gym Equipment	40.64	105-Miscellaneous manufacturing

HT/LT-High tension/Low tension, DG set-Diesel generating set, UPS-Uninterrupted power supply

4.2.7 EE coefficients used for estimation of IEE: India (base case) and Australia

In the international scenario, the Australian database for EE coefficients is comparatively better developed as compared to other countries. Therefore, to analyse the effect of geographical representativeness, the IEE of the building project was computed with Indian EE coefficients as the base case and then compared with IEE estimations using Australian EE coefficients. EE coefficients of some important material based on the Indian economy (base case) and the Australian economy used to estimate EE are placed in **Table 4.5.** EE coefficients based on the Indian and Australian economy are found to vary from approximately 2% (Marble stone) to 320% (Copper).

Table 4.5 Comparison of embodied energy coefficients of materials

Main Material	**Unit**	**EE Coefficients (India) (Base Case) (GJ/unit) (A)**	**EE Coefficients International (Australia) (GJ/unit) (B)**	**Variation between (B) and (A) (%)**
Steel	Ton	38.00	85.46	124.89
Cement	Ton	6.40	16.96	165.00
Cement concrete	m^3	2.09	5.01	139.71
Bricks-clay	Ton	3.60	3.50	-2.78
Stone marble	Ton	16.61	16.30	-1.87
Granite	Ton	18.09	16.30	-9.91
PVC	Ton	55.00	156.90	185.27
Laminated wooden flooring	m^3	27.18	9.61	-64.64
Plywood	m^3	18.00	30.35	68.61
Ceramic tiles	Ton	8.20	11.98	46.13
Synthetic enamel paint	Ton	144.00	124.00	-13.89
Gravel /Aggregate	Ton	0.11	0.36	227.27
Bitumen	Ton	13.72	46.52	239.17
Aluminium	Ton	310.00	358.00	15.48
Copper	Ton	90.00	378.90	321.00
Glass-float	Ton	17.00	28.50	67.65
Concrete roof tiles	Ton	13.00	4.300	-66.92
Sanitaryware	Ton	37.90	98.00	158.58

Sources: Australia data - Crawford (2011), Crawford et al. (2019). India data - IFC (2017) , Maini and Thautam (2009), Shukla et al. (2009), Computations from Input-Output Table 2013-14

4.3 RESULTS

Initial EE incurred by the sub-systems during the pre-occupation stage includes EE due to extraction and processing of raw material, transportation of raw material from quarry to material production site (manufacturing industry), production of material, transportation of material from manufacturer to construction site and employment of labour and machinery during the actual construction of sub-systems.

In addition, indirect energy is consumed in administrative and technical activities performed during the building project's pre-design, design and construction phases. Details of cost elements that contributed towards indirect embodied energy in the pre-occupation stage are placed in **Table 4.6.** The share of this indirect energy was allocated to the sub-systems in proportion to their initial cost. EE incurred on administrative and technical activities in the pre-design and design phases worked out to be 2.83% of the total IEE. Similarly, EE consumed on administrative and technical activities during the construction phase is estimated to be 13.57% of the total IEE. Thus, the total EE incurred on account of administrative and technical activities during the pre-design, design and construction phases is estimated as 16.40% of the total IEE incurred during the pre-occupation stage, which most studies have generally ignored in the past.

Table 4.6 Administrative and technical costs during the pre-occupation stage

Phase of pre-occupation stage	**Cost element**
Pre-design phase	Cost of the technical team for preliminary planning - project conception at the macro level, financial feasibility check
	Site survey
	Soil investigation
Design phase	Developer head office team (planning, design, contract, procurement) salary
	Cost of design consultancy- architectural, structural, MEP, others
	Government approvals
	Insurance cost
Construction phase	Developer site team salary (project manager, site engineers (civil works and MEP)
	Cost of project management consultancy (PMC)
	Overheads - cost of office expenses, maintenance of arboriculture and security
	Cost of marketing and brokerage for residential property
	Escalation cost due to project delay

The share of each sub-system and the total IEE of the building project in the pre-occupation stage is shown in **Figure 4.2**.

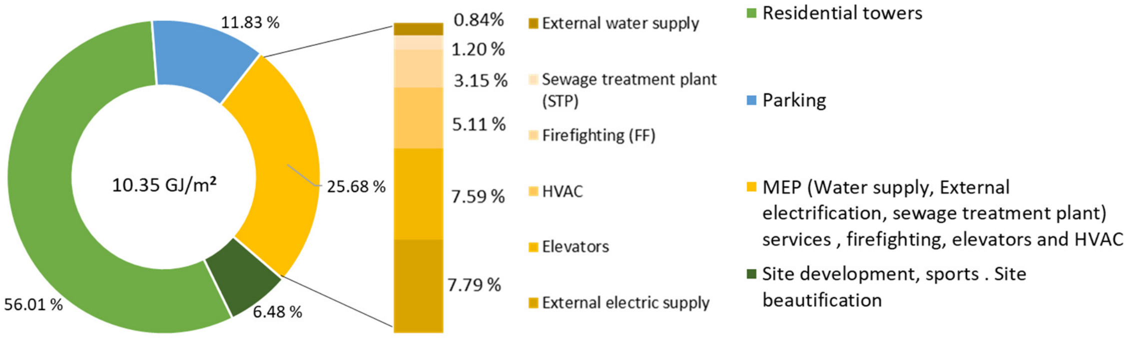


Figure 4.2 Share of initial embodied energy of sub-systems

In Figure 4.2, the IEE of the building project has been computed using Indian EE coefficients as shown in Table 4.4 and Table 4.5 to ensure geographical correlation of the data used for estimation of IEE. Table 4.4 contains the list of items whose embodied energy is calculated using the I-O analysis method of the Indian economic sectors. On the other hand, Table 4.5 gives out the details of items whose embodied energy is determined based on product of energy coefficients and material quantities. Similarly, the requirement of temporal correlation of data was met using the most current EE coefficients available from the year 2009 to 2017 (Zulcão et al., 2020).

Most studies in the past conducted the energy analysis of the building portion only while MEP sub-systems and site features were mostly excluded. Therefore, the contribution of various construction material in the total weight has been computed for the building portion only as shown in **Figure 4.3** to enable comparison with other studies,

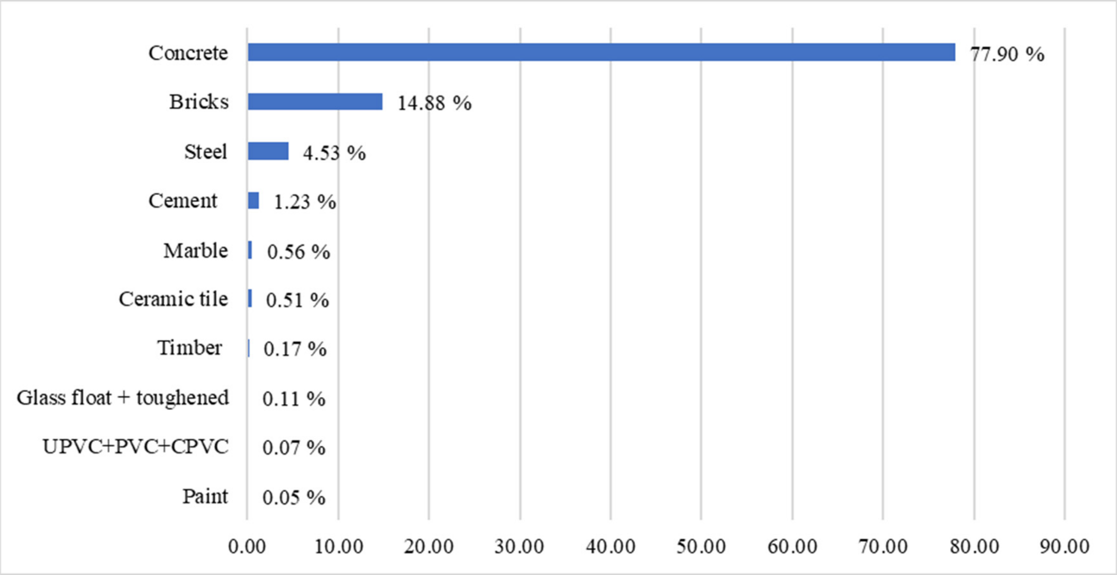


Figure 4.3 Contribution of main material in total weight of building portion excluding MEP & site features

4.4 DISCUSSION

4.4.1 The initial embodied energy of sub-systems

Among the sub-systems, residential towers consumed the highest IEE (56.01%) as it is the largest of all the sub-systems, and it utilised the maximum portion of the building material for the construction of RCC framed structure, joinery, flooring and finishes. The parking sub-system, which consists of basements, consumed the second highest IEE (11.83%). MEP services (which include external water supply, external electric supply, sewage treatment plant (STP), firefighting (FF), elevators, and HVAC) together consumed 25.68% of the total IEE of the building project system. Thus, MEP services and site development features (comprising site development, sports, and site beautification sub-systems), which were generally ignored by previous studies, together accounted for 32.16% of the total IEE, and this aspect deserves due attention. The energy footprint during the pre-occupation stage due to the total IEE of all sub-systems has been estimated as 16,88,958.18 GJ or 10.35GJ/m^2 **(Figure 4.2)** i.e., 57.5 kWh/m^2/year.

4.4.2 Comparison of initial embodied energy using Indian and international embodied energy coefficients

Embodied energy is stated to be dependent on the geographic location of the buildings. The reason for this variation is due to differences in the quality of raw material, industrial production processes and their efficiency, logistics, climate, construction practices, energy mix, the efficiency of energy infrastructure (production, distribution), and energy tariffs (Buchanan & Honey, 1994; Grazieschi et al., 2020; Holtzhausen, 2007). To examine the effect of geographical representation, the initial embodied energy of the building portion was computed using Indian EE coefficients as a base case and then compared with that using international EE coefficients from Australia (**Table 4.7**).

Table 4.7 Initial embodied energy using Indian and international EE coefficients

	Unit	Using EE coefficients (India) (Base Case) (A)	Using EE coefficients International (Australia) (B)	Variation between (B) and (A) (%)
IEE of building portion (Tower + Basement)	GJ/m^2	7.02	11.97	70.53
	kWh/m^{2}y	39.01	66.52	70.53

IEE of the case study building with international EE coefficients is found to be higher than the values computed using Indian EE coefficients by nearly 71%. In an earlier study, Devi and Palaniappan (2014) found that the IEE of a case study building with EE coefficients from the UK resulted in lower values than that estimated using Indian EE coefficients by 25%. Thus, lack of geographical representativeness may result in indication of erroneous i.e., higher or lower values of embodied energy for buildings in a given country, leading to inaccurate comparison with similar studies.

4.4.3 Mass vs. embodied energy of main materials

The main materials normally used in building construction could be broadly categorised into steel, concrete, bricks and cement. In the present case study building project, these materials, which make up 98.54% of the total weight, also contribute to 90.27% of the total initial embodied energy during the pre-occupation stage. However, the EE of these four main materials is found to be disproportionate to their corresponding share by weight. **Figure 4.4** shows the relative proportion of mass versus embodied energy of main materials in the building portion. It could be observed that steel contributed the highest share of embodied energy, around 58.52% of the embodied energy, due to the very high energy intensity of the steel sector, though the weight of steel used is only 4.53%, On the other hand, concrete had the largest share of weight (around 77.90%), but the share of embodied energy is about 23.20%, which is much lower than that of steel. The low embodied energy of concrete is due to higher proportions of coarse and fine aggregates (both materials having comparatively low values of embodied energy) and lower proportions of cement. Bricks contributed towards 14.88% and 5.87% of total weight and initial embodied energy, respectively. On the other hand, cement showed a share of 1.23% by weight but contributed 2.68% of the total initial embodied energy owing to the higher energy intensity of the cement production process. The pre-dominance of envelope materials like steel, concrete and bricks in the total EE of the building portion is in agreement with past studies such as Asif et al. (2007) and Blengini (2009), subject to some variation due to differences in structural requirements depending on geographical location (earthquake zone, climate), height of buildings and presence of underground structures (basements).

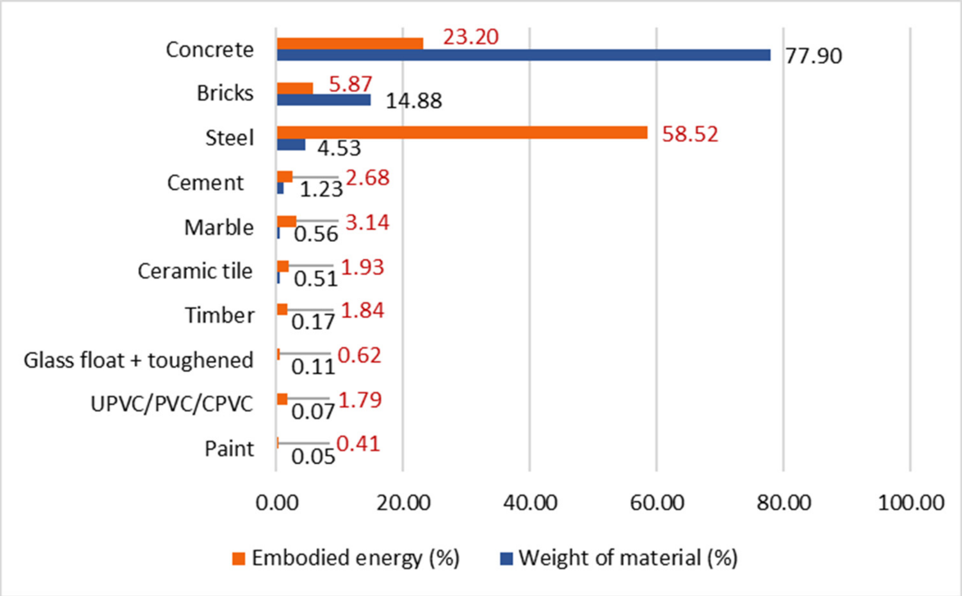


Figure 4.4 Proportion of mass vs proportion of embodied energy of main materials in building portion

4.4.4 Suggested measures for the reduction of embodied energy

The significance of embodied energy has increased in modern buildings due to the greater thrust to minimise the operational energy, especially in low-energy buildings. One of the strategies to fulfil this objective is to review the usage of materials in buildings from an embodied energy perspective. It could be observed from the review of materials usage patterns that steel, concrete and bricks are among the largest contributors towards the total embodied energy of the building project system. As steel accounted for the highest share (>58%) of the total EE in the building portion, it is recommended that recycled steel may be used in place of virgin steel since the embodied energy coefficient of recycled steel is nearly 30% lower than that of virgin steel (Chen et al., 2001).

Another suggested method to decrease the embodied energy of buildings is to reduce the quantity of concrete usage by using composite material comprising structural steel and concrete for the construction of building structure. The advantage of using more steel over concrete lies in the fact that embodied energy is recovered on recycling of steel, whereas additional embodied energy is expended for recycling of concrete into recycled products. Moreover, composite structures may also favour the design for disassembly approach by appropriate design of joints between structural steel members and pre-fabricated concrete material, thereby leading to reduction of energy required during construction and demolition stages. Similarly, the embodied energy of bricks can also be decreased by using alternate materials such as cavity blocks and concrete blocks, which are manufactured by replacing certain portion of cement with fly ash. Another suggested technique for reducing embodied energy is to replace the frame and brick wall construction with shear walls.

Additionally, there is a need to re-examine the practice of promoting vertical construction in the form of tall buildings. Taller buildings are reported to result in higher embodied energy and embodied greenhouse gas emissions due to the increase in the size of structural members to resist higher wind and earthquake loads (Foraboschi et al., 2014; Gunel & Ilgin, 2007; Treloar et al., 2001a). Therefore, energy analysis of compact development as obtainable in high-rise residential complexes may be compared to spread-out low-rise residential complexes, and town planners may consider the findings for reducing the environmental burdens (energy footprint) of future developments.

Another important issue is the accuracy, completeness and availability of data on building materials and construction details. The embodied energy analysis is highly data intensive. During the study, it was observed that no formal data repository or mechanism exists in India that can be accessed for research on building energy. Moreover, developers and project managers are reluctant to share data on building construction, citing legal, commercial and proprietary concerns. This may lead to inaccuracies in data and results due to assumptions made by researchers. This points towards the requirement of a suitable policy framework on mandatory archiving and sharing of data at the urban local authority (ULB) level to greatly assist the research environment.

It is also observed in practice that a large number of residents usually resort to additions/alterations in building partitions and upgradation of kitchen and sanitary fixtures, joineries and floor finishes immediately on taking possession of their apartments from the developer, thus leading to further increase in initial embodied energy. Therefore, undue increments in embodied energy can be obviated if developers provide options for limited customisation of apartments to owners during the initial construction.

4.5 SUMMARY

The aim of this chapter was to carry out the energy analysis of the building project at the pre-occupation stage. The analysis attempted to cover certain important gaps in previous studies pertaining to system boundary selection in terms of stages and sub-stages of the life cycle, components of the building project, and geographical representativeness. In particular, the initial embodied energy (IEE) of the building project during the pre-design, design, and construction sub-stages was estimated. Data was collected in the form of contract documents, drawings and purchase orders from multiple sources of evidence: developer, contractors, suppliers, consultants, project managers, senior engineers, and literature. Data verification was accomplished through direct observation and technical discussion with senior site engineers and project management during the site visits to the building project.

The energy analysis was conducted using the input-output hybrid analysis method. To examine the significance of geographical representativeness, the variation in IEE of the building portion with Indian embodied energy coefficients and Australian embodied energy coefficients was computed. Additionally, India specific embodied energy coefficients were developed using the input-output table of the Indian economic sectors for certain construction materials/components, which were not available in the public domain. The findings of this study indicate that the residential tower sub-system contributed to the highest share of IEE, followed by MEP sub-systems. Steel, concrete, bricks and cement together accounted for most of the total weight of construction material and total IEE during the pre-occupation stage. In conclusion, some measures for reduction in IEE have been suggested.

CHAPTER 5: ENERGY ANALYSIS OF OCCUPATION STAGE

5.1 INTRODUCTION

The '*occupation stage*' of a building commences after the building gets occupied upon completion of construction and ends when the building is vacated for demolition. This stage is also known as the '*use stage*' or the 'operating stage' or the '*operation stage*'. During the occupation stage, the building consumes two types of energy: recurring embodied energy (REE) and operation energy (OE). REE is consumed on (a) replacement of sub-system components and (b) repair and maintenance (Cherian et al., 2020). Whereas OE is incurred on lighting, use of domestic appliances, heating, ventilation and air conditioning (HVAC) functions, and operation of services and their management (Abbasabadi & Ashayeri, 2019).

The REE expended in repair, maintenance and replacement would depend upon numerous factors such as composition of material, type of usage, climatic conditions, and change in technology (Marzouk & Elshaboury, 2022). Similarly, at the macro level, the intensity of operating energy requirement will be affected by the local climate and seasonal variations, the nature of building use/function, and the type and number of electro-mechanical equipment installed (D'Agostino et al., 2023). Whereas, at the micro level, the OE requirement may be influenced by a number of factors such as building form, building geometry (shape, size), orientation, and building envelope characteristics (e.g., type of building material used, window to wall ratio). Additionally, the results of operating energy analysis would also differ due to the use of different methods for energy estimation (Andrić et al., 2019).

Some studies expressed operating energy results in terms of final (end-use) energy. However, such results may lack comparability due to differences in the energy mix and efficiency of power generation of various countries. To overcome such shortcomings, it is preferable to use primary energy to indicate the operating energy consumption by using a conversion factor, also known as primary energy factor (Gibbons & Javed, 2022).

Regarding the scope of studies, most studies only considered the energy demand for cooling and heating of buildings, assuming it to be the dominant portion of the total operating energy consumption (Frayssinet et al., 2018; Sadineni et al., 2011). A few studies also included electrical appliances as part of their scope of research (Hoxha & Jusselme, 2017; Rossi et al., 2012). Whereas, most studies excluded the MEP services and site features (Huang et al., 2018; Takano et al., 2015) from the scope of their research while estimating the OE demand of building projects, thus leading to inaccuracies in the findings. However, accuracy in the estimation of OE is vital for the application of measures for reduction (Rauf & Crawford, 2015) in the total OE consumption of a building project.

The aim of this chapter is to study the energy demand of a high-rise residential building project during the occupation stage. The current study has considered the complete system boundary in terms of the life cycle stages and the components of the building project, including MEP services and site features. The REE of the building project has been estimated using input-output hybrid analysis, whereas the operating energy has been computed by direct measurement method based on energy meter records maintained by facility management.

5.2 MATERIAL AND METHODS

5.2.1 Method used for energy estimation during the occupation stage

The methods used by past studies for the estimation of the operational energy demand of buildings include a) prediction methods such as the steady-state and dynamic energy simulation methods, b) use of pre-recorded databases for a particular type of building (reference buildings), and c) direct measurement methods which involve use of actual energy consumption records ascertained from energy bills (Atmaca & Atmaca, 2015).

A large number of studies utilised energy simulation software such as TRNSYS (Klein et al., 2007), EnergyPlus (Crawley et al., 2000), DOE-2 (Booten et al., 2012) and eQuest (Hirsch, 2023) for the prediction of operating energy consumption, at the design stage. However, the simulation methods are resource-intensive and are generally incapable of accommodating dynamic factors such as weather and occupant behaviour (Sonta et al., 2018). Some studies have asserted that the dynamic thermal behaviour of the building envelope is likely to cause a large variation in the predicted energy demand for the operation of buildings (Aste et al., 2015). Moreover, these methods are dependent on the quality of input data, which may not be available at the design stage (Bourdeau et al., 2019). More importantly, large gaps may occur between the predicted and actual operating energy consumption (Mikhail et al., 2023; Wenninger et al., 2022). Therefore, some studies proposed the use of ‘in situ modelling’ (Yoon, 2023) or ‘longitudinal prediction’ (de Wilde et al., 2011) throughout the operation stage for improvement in energy simulation tools. But, since the operation stage is usually 50 to 100 years long, any further utilisation of findings from such methods is likely to be available only in the distant future. Additionally, several studies proposed using BIM for seamless monitoring and management of built assets during the occupation phase (Jrade & Jalaei, 2013).

Some countries have regulated the measurement of the energy demand of buildings in comparison to pre-recorded databases for each type of reference building for ensuring standardisation and comparability, e.g., the Directive 2010/31/EU of The European Parliament (Corgnati et al., 2013), and United States Department of Energy (Deru et al., 2011). However, as the building construction industry is dynamic in nature with continuous developments in methods of design, construction technology, construction material, and energy efficiency of electro-mechanical equipment, frequent updating of reference building models would be required.

The direct measurement method uses the data on operating energy consumption taken directly from energy meter readings or from the energy bills received from energy distribution companies (DISCOMS) or the facility management (Geng et al., 2018). These methods have the advantage of depicting the actual behaviour of buildings and also do not require any data for energy estimation, unlike prediction methods, which use energy simulation tools (Chang et al., 2019). Energy prediction methods can be used for new as well as existing buildings. On the other hand, direct measurement methods are useful mainly for existing buildings but do not require calibration to improve accuracy, unlike prediction methods (Yoshino et al., 2017). On the other hand, disaggregation of data would be required to allocate energy burdens to building sub-systems when energy bills are used for data collection (Wang et al., 2012).

Based on the strengths and shortcomings of various methods for the estimation of energy demand during the occupation stage, as discussed above, the input-output hybrid analysis method has been used for estimating the REE. On the other hand, the direct measurement method has been used for the computation of OE.

The steps followed for the estimation of energy consumption during the occupation stage are as follows:

- System boundary selection and data collection.
- Estimation of REE consumption due to the replacement of building material and components in each sub-system.
- Computation of REE expended on repair and maintenance of the sub-systems.
- Estimation of OE consumption for operation of the sub-systems.

Each of these steps is discussed in the following sub-sections.

5.2.2 System boundary selection and data collection

The system boundary selected for the occupation stage of the case study project, described in Chapter 3 – Research Methodology, with respect to the building project components, and the sub-stages of the life cycle comprises the sub-stages B1 to B6, as shown in **Figure 3.1 (Chapter 3)**. In this system boundary model, sub-stage B7 pertaining to operational water use has been excluded from the scope of the study as this study has focused on the energy analysis of the building project. With respect to the case study building project, the direct and indirect energy consumed during the occupation stage are as follows:

a. Recurrent energy consumed on account of use, maintenance, repair, replacement, and refurbishment (sub-stages B1 to B5 of the building project life cycle)

b. Direct operational energy consumed on account of power consumption on lighting and operation of appliances and MEP services (sub-stage B6). In addition, indirect operational energy is also consumed on the cost of management of facilities, in terms of providing technical and administrative personnel, security staff, housekeeping, procurement of expendables such as chemicals for water treatment plant and sewage treatment plant, hygiene and sanitation chemicals for housekeeping, and miscellaneous activities such as building insurance, and licence fee for running of swimming pool.

Data on the service life of building materials/components was collected from literature such as past studies, maintenance manuals, original equipment manufacturer's (OEM's) specifications and environment product declarations (EPDs). Data on the cost of repair and maintenance of sub-systems/components was extracted from annual maintenance contracts (AMCs) and industry benchmarks from facility manager and literature such as CPWD Manuals (CPWD, 2019). The CPWD Delhi Schedule of Rates are revised periodically, can be fairly relied upon and has also been used by many researchers, e.g., Vyas and Jha (2017), Mastrucci and Rao (2019), and Bansal et al. (2021). Data on power consumption for lighting and operation of MEP services was collected from the energy meter records of the facility manager. Similarly, data on building insurance and the cost of administrative and technical manpower employed for the operation, maintenance and security of the building project was collected from the facility management in the form of documentary evidence.

Site visits were undertaken to verify the data, and this was corroborated by discussion with the facility manager and administrative and technical supervisors to crosscheck the type and number of equipment, their power ratings, average hours of operation per day and deployment of manpower.

5.2.3 Method used for the computation of replacement EE

Replacement of certain sub-system components is inevitable as the building life span outlives the designed or actual service life of these components and, secondly, to ensure their reliability to provide the desired services or functions without degradation of efficiency. A number of past studies have assumed the recurrent embodied energy of buildings as a proportion of initial embodied energy for the sake of simplification, e.g., 20% by Fuller and Crawford (2011). However, this study considers the service life of the building components to obtain a more realistic assessment of recurrent embodied energy. There is no consensus amongst past studies on the service life of building materials and equipment. To elucidate further, details of the service life of different materials assumed by some previous studies and the service life considered for this study are shown in **Appendix C**.

The embodied energy incurred on the replacement of building material or components was estimated in two steps: a) computation of cost of replacements, and b) estimation of embodied energy used on the replacements. The replacement cost of components was calculated based on the expected service life of components over the entire life span of the building. The building life span has been assumed to be 50 years for this study. The no. of replacements (Replacement Factor) required for a component is given by Equation (Eq) (1): -

$$N = \text{ROUNDUP}(\text{IF}((L_B/L_C-1)<0,0,(L_B/L_C-1)),0) \tag{5.1}$$

Where N= Total estimated no. of replacements of a building component during the building life span

L_B = Building life span in years

L_C = Service life of building component under consideration in years.

In case the last replacement occurred when the residual life span of the building is less than or equal to 35 per cent of the service life of the component, the estimated no. of replacements was modified and reduced by 1 (one), as such replacements are considered to be uneconomical. A similar modification was also carried out when the residual life of the building after penultimate replacement was less than or equal to 5 years. However, no such modification was done if the component is found essential from safety, security or reliability of essential services considerations.

Thereafter, EE due to replacements was computed using the Input-Output Based Hybrid Analysis Method (Crawford & Treloar, 2003; Lenzen, 2000) in a similar manner as adopted for IEE estimation during the Pre-occupation Phase of the building (Chapter-4). The replacement EE is given by Eq (5.2) and Eq (5.3) (Crawford et al., 2016) below:-

$$\mathrm{EE}_{\mathrm{repl}} = \sum_{i=1}^{n} \mathrm{EE}_{\mathrm{repl}}\,(i) \tag{5.2}$$

$$\mathrm{EE}_{\mathrm{repl}}\,(i) = \sum_{m=1}^{M} \mathrm{N}\,(Q_m \times EC_m) + (TER_n - TER_m - TER_{mn})\mathrm{x}\, C_{mi} \tag{5.3}$$

Where,

$\mathrm{EE}_{\mathrm{repl}}$ = Replacement embodied energy of the building in Giga Joules (GJ)

$\mathrm{EE}_{\mathrm{repl}}\,(i)$ = Replacement embodied energy of sub-system *i* in Giga Joules (GJ)

Q_m = Quantity of each material m replaced during each replacement

EC_m = Embodied energy coefficient of material m per unit quantity

TER_n = Total energy requirement of construction sector in GJ per Rs Lakhs

TER_m= Unique sectoral energy requirement of material production for which process data is available in GJ per Rs Lakhs

TER_{mn} = Total energy requirement of material not related to installation or production of the material under replacement in GJ per Rs Lakhs, for example total energy requirement of steel production while replacing sanitary fixtures

C_{mi} = Total cost of all materials being replaced in the sub-system *i* in Rs Lakhs

N = Replacement factor of each material m being replaced as given by Eq (5.1) above.

The replacement factor (N) of material /components of each sub-system used for estimation of replacement cost is placed in **Tables D-1 to D-11** of **Appendix D.**

5.2.4 Method used for computation of EE on repair and maintenance

Building project components require routine repairs and maintenance to ensure that each component is maintained in good condition throughout its service life so that the building project not only survives its designed or expected life span but also helps in prolonging the same.

Initially, the cost incurred on repairs and maintenance of all sub-systems has been computed based on (a) Annual Maintenance Contracts (AMCs), (b) historical data or experience of Facility Management (FM) organisations and (c) Plinth Area (PA) Rates for civil engineering and electrical engineering maintenance from CPWD (2019). Cost elements considered for computation of EE required for repair and maintenance (EErepair) of all sub-systems are shown in **Table D-12** of **Appendix D**. Currently, the EE consumption on repair and maintenance (EE_{rm}) is estimated based on the cost of repairs and maintenance, and sectoral energy intensity computed from Input-Output Tables (Crawford & Treloar, 2005) as given by Eq (5.4).

$$EE_{rm} = \sum_{i=1}^{n} EE_{rm}(i) \tag{5.4}$$

Where:

$EE_{rm}(i)$ = Embodied energy consumed on repair and maintenance of each sub-system i in Giga Joules (GJ).

5.2.5 Method used for OE estimation

Major approaches used in past studies to estimate the operational energy demand of buildings include a) actual energy consumption records ascertained from energy bills, b) use of e-recorded databases for a particular type of building and c) use of steady-state and dynamic energy simulation methods (Atmaca & Atmaca, 2015). Additionally, some studies have used a combination of Building Information Modelling (BIM) and energy simulation tools, which have the advantage of enabling LCEA at the design stage for finding optimum energy design alternatives. However, as discussed earlier, large gaps exist between predicted and actual OE consumption.

Therefore, field measurement or site survey methods, which are more accurate, have been selected in the current study for OE estimation of the building project which is already in use by occupants (Wagner et al., 2014). Data on power consumption, expenditure on consumables and deployment of human resources for the operation of the building project were collected from facility management strictly on conditions of confidentiality. To ensure the accuracy of data, the power rating of each equipment under use and average number of hours of operation and deployment of manpower were ascertained through unstructured interviews with the facility manager and key personnel such as technical manager, security officer, fire and safety officer, housekeeping supervisor, pump operators and electricians.

The power consumption data collected on residential apartments showed the combined power consumed on lighting, appliances and HVAC (Air conditioners) due to a single metering system. Therefore, the power consumption on lighting and appliances was estimated based on the method suggested by (Hoxha & Jusselme, 2017) (**Table 5.1)** and subtracted from the total power consumption of apartments to obtain the power consumption of the sub-system. The lighting load of the common areas in residential towers, such as the lift lobby, staircase and entrance, was combined with the elevator sub-system due to the common metering of these loads. The operating energy (OE) of each sub-system is given by Eq (5.5).

$$\mathrm{OE} = \sum_{i=1}^{n} \mathrm{OE}\,(i) \tag{5.5}$$

Where:

$\mathrm{OE}\,(i)$ = Operating energy of each sub-system *i* in Giga Joules (GJ)

5.2.6 Energy consumption during the occupation stage

The total energy consumed during the occupation stage (E_{occ}) is the sum of recurring embodied energy (REE) and operating energy (OE) as given by Eq (5.6). Where REE is the energy consumed on replacements (EE_{repl}), and repair and maintenance (EE_{rm}) as given by Eq (5.7).

$$E_{occ} = REE + OE \tag{5.6}$$

$$\text{Where, } REE = EE_{repl} + EE_{rm} \tag{5.7}$$

Table 5.1 Lighting and appliance load in residential apartments

	Nos/ house	**Rating**	**Source/ Reference**
LCD television	1	1167 MJ/year	#
Laptops	2	39 MJ/year/ laptop	#
Microwave oven	1	518 MJ/year	#
Refrigerators medium size	1	3105 MJ/year	#
Washing machine	1	518 MJ/year	#
Vacuum cleaner	1	65 MJ/year	#
Lighting luminaires	-	24.5 MJ/m^2/year	#
Ventilation fans, exhaust fans	-	14 MJ/m^2/year	#
Geyser	2	2592 MJ/year/ geyser	$$

#-Hoxha and Jusselme (2017), $$ - Assumed

5.3 RESULTS

5.3.1 Recurring energy

The share of the recurring EE of sub-systems, i.e., the total of Replacement EE and Repair and Maintenance EE, is shown in **Figure 5.1**. It could be observed that MEP sub-systems contribute about 47% of the total REE of all sub-systems, which is the largest share amongst the sub-systems.

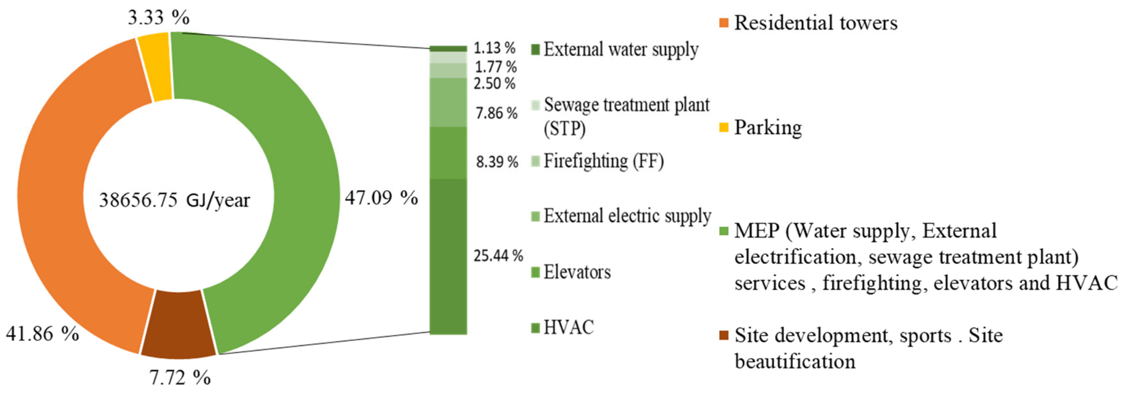


Figure 5.1 Share of recurring embodied energy of sub-systems

The sub-system-wise proportion of IEE and REE with respect to the total of IEE+REE is shown in **Figure 5.2**. It could be observed that the Recurring EE of the Vehicle Parking Sub-system with respect to its Initial EE is the lowest (32.21%), and that of the HVAC Sub-system is the highest (569.62%). The reason for such large variation is primarily due to the absence of components/parts requiring frequent replacements in the case of the vehicle parking sub-system. The vehicle parking sub-system is a RCC structure (Basements) **(Table D-5** of **Appendix D),** while the HVAC sub-system needs frequent replacements, and it also incurs a high cost of maintenance **(Table D-6** of **Appendix D).**

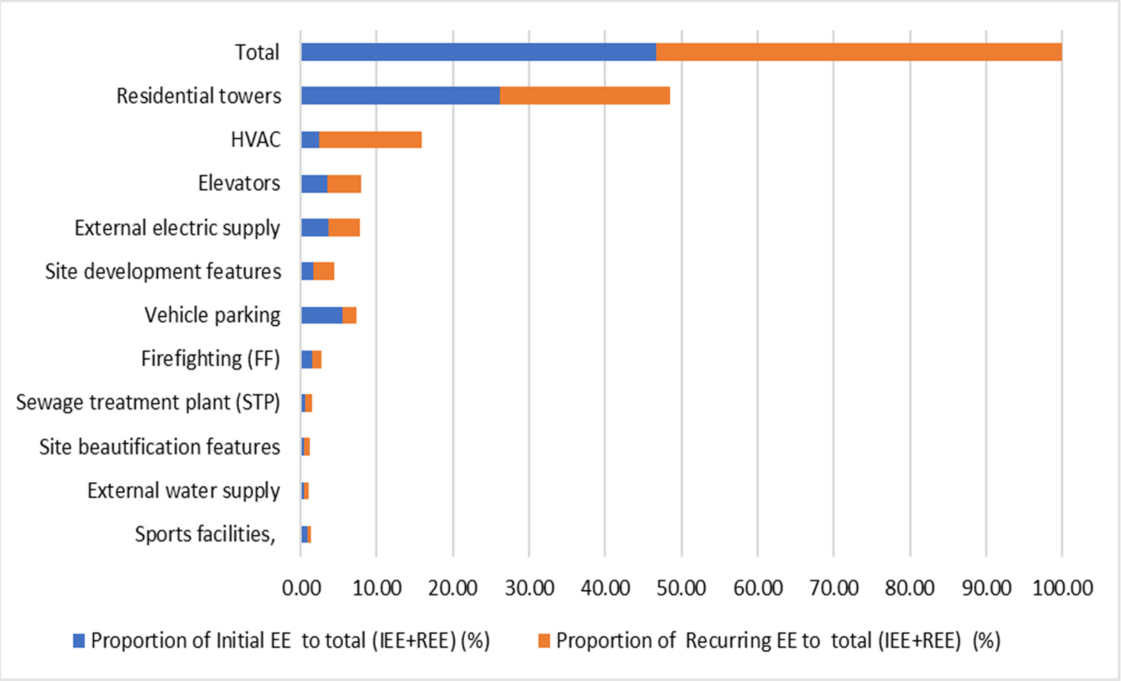


Figure 5.2 Proportion of IEE and REE in total of IEE+REE of all sub-systems

5.3.2 Operating energy

The operational energy of sub-systems has been computed based on the data collected from the field. Indirect OE consumption due to expenditure on common facility management services, such as establishment cost and cost of technical services, which could not be clearly delineated to a particular sub-system, was allocated proportional to the initial cost of the sub-systems **(Table D-13** of **Appendix D)**. In the case of the external electrification sub-system, power is consumed due to losses in the power distribution system, which has been computed based on (BEE, 2015; Ministry of Power, 2016). The share of operating energy consumed by the sub-systems in terms of primary energy is shown in **Figure 5.3.**

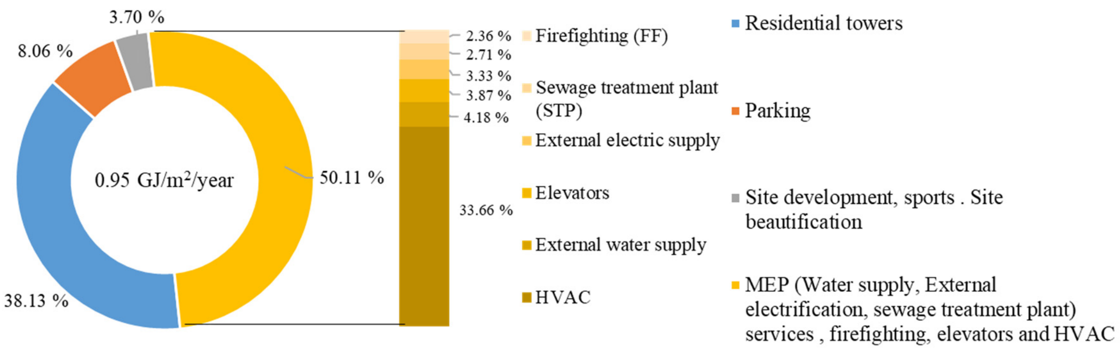


Figure 5.3 Share of operating energy of all sub-systems

It is observed that unlike the pre-occupation stage where the embodied energy consumption was dominated by the residential tower sub-system, in the occupation stage, MEP sub-systems have accounted for the highest share of operating energy demand (**Figure 5.3**). The reasons for the above seem justified as operating energy is required by residential towers only for lighting and operation of appliances. On the other hand, MEP sub-systems accrue operating energy consumption for provision of all services such as external water supply, external electric supply, sewage treatment, operation of elevators, maintenance of water pressure in the firefighting system, and operation of HVAC equipment.

5.3.3 Energy consumed during the occupation stage

The total energy consumption during the occupation stage is the sum of REE and OE consumed by all sub-systems as computed above. The proportion of REE and OE to the total REE+OE of all sub-systems is shown in **Figure 5.4.** As seen from this figure, the OE accounts for the major share of the total energy consumption by each sub-system during the occupation stage. At the building project level, the OE of all sub-systems collectively contributed to nearly 80% of the total energy demand during the occupation stage while REE of all sub-systems accounted for the remainder 20%. During the operation stage, the REE and OE consumption of all sub-systems were found to be 65.81 kWh/m^2/year and 264.61 kWh/m^2/year, respectively. The energy footprint of the operation stage has been estimated to be 330.42 kWh/m^2/year.

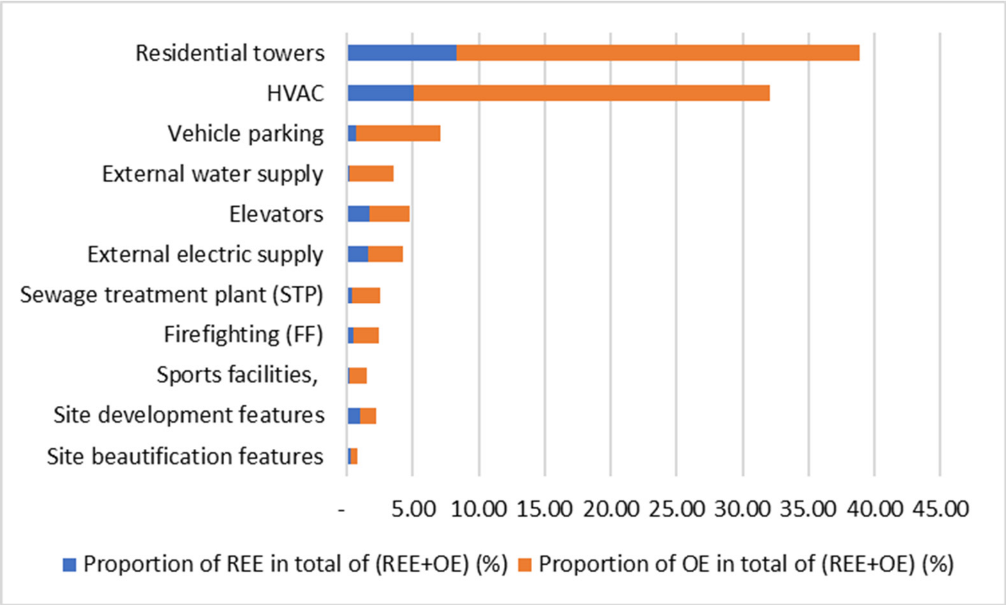


Figure 5.4 Proportion of REE and OE in total of REE+OE of all sub-systems

The operating energy of sub-systems with respect to initial EE is shown in **Figure 5.5.** It may be noted that the relative proportion of operating energy of certain sub-systems with lower initial EE such as HVAC, sewage treatment plant and external water supply, is found to be higher than that of other sub-systems with higher initial EE for instance in case of residential towers and vehicle parking sub-systems.

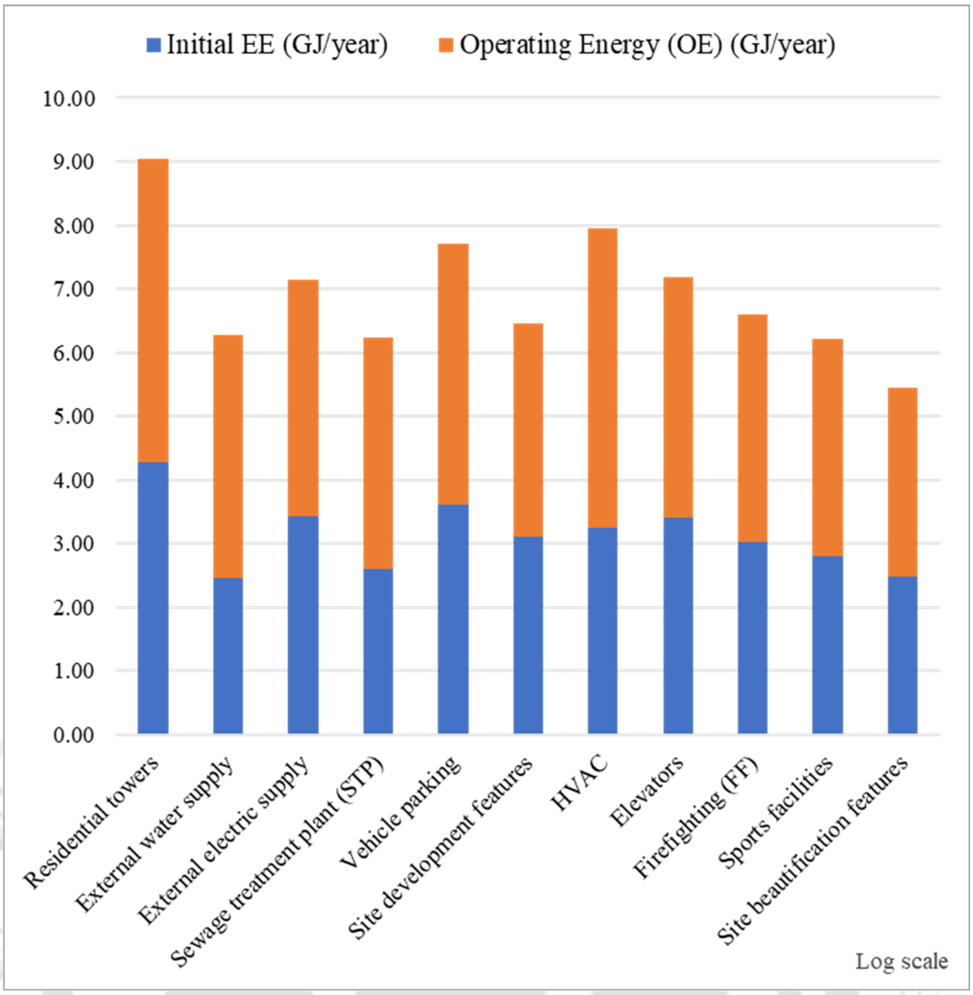


Figure 5.5 Initial EE vs operating energy of sub-systems

5.4 DISCUSSION

In the current study, the proportion of REE with respect to IEE in the case of MEP services, site development, and site beautification sub-systems was found to be comparatively higher than that of residential towers, parking, firefighting and sports facilities sub-systems **(Figure 5.2)**. This could be attributed to the higher frequency of replacements of materials/components of those sub-systems. This emphasises the need to examine the cost versus durability of the affected materials//components at the time of replacements, apart from other factors such as implications during other stages of the building life cycle. In addition, the feasibility of overhauling/refurbishing MEP equipment by OEMs may be explored as a cheaper and low-energy option compared to outright replacements. For instance, Kirloskar Brothers Limited (KBL), Pune, has commissioned a few authorised refurbishment centres (ARCs) across India to refurbish various types of pumps they manufacture (KBL, 2023). Similarly, remanufacturing of equipment such as power generator sets can save up to 85% of the energy required for new products in case of part replacements.

5.4.1 Comparison with previous studies

As per the present study, the annual REE has been estimated to be about 2.28% of IEE, which is reasonably in agreement with values of 2.3% and 2.8% estimated by Humphrey et al. (2004) and Langston (2006), respectively. Furthermore, the total REE of all sub-systems is found to be slightly more (nearly 1.14 times) than IEE. Some previous studies have reported large variations in REE, ranging from 0.73 to 1.99 times of IEE (Ding, 2007), with an average value of REE as 1.08 times of IEE. The variation in REE values between this study and the previous studies could be justified due to differences in the type of building, type of construction material used, periodicity of repair and maintenance, number of material replacements (Rauf & Crawford, 2015), life span of buildings, and system boundaries considered in the past studies (Mourao et al., 2019). At, the same time it may be worth highlighting that the REE results may also vary due to the type of method used (e.g., process analysis, input-output analysis or input-output hybrid analysis) for REE estimation.

In the current study, the total annual OE of the building project has been estimated to be nearly 155439.41 GJ/year (i.e., 264.61 kWh/m^2/year). Out of which, building related sub-systems (residential tower and parking sub-systems) and non-building sub-systems (MEP services, firefighting, HVAC, site development, sports, and site beautification sub-systems) consumed 46.19% and 53.81% of the total operating energy requirement of the building project, respectively **(Figure 5.3)**. Amongst the MEP services, HVAC contributed the highest proportion of operating energy (33.66%) due to high power consumption on space heating and cooling requirements. On the other hand, the firefighting sub-system required the lowest proportion of operating energy (2.36%) due to minimum requirements of pumping operation for pressure maintenance in the firefighting system. The firefighting sub-system consumes lower operating energy as it remains dormant for most of the time except during actual fire incidents or during periodic testing and firefighting practices conducted by the facility manager/resident management.

The OE computed by this study is found to be in variance with some earlier studies. For instance, the OE consumed for residential buildings was estimated as 19-35 kWh/m^2/y by Mithraratne and Vale (2004) in New Zealand, 171-174 kWh/m2/y by Ramesh et al. (2012b) in India, and 274 kWh/m^2/y and 328 kWh/m^2/y by Rossi et al. (2012) in Belgium and Sweden respectively.

A close scrutiny of the above studies reveals that the reasons for variation in the OE values are mainly due to differences in system boundaries selection, prevailing climate, building envelope material, and method used for OE computation. To elucidate further, the study by Mithraratne and Vale (2004) pertains to standalone houses with wall and roof insulation located in the subtropical to subantarctic climate of New Zealand but included the building portion only while excluding the MEP services and site features. Moreover, the results of OE by Mithraratne and Vale (2004) are quite low compared to all other studies, as they have been shown as final energy instead of primary energy. Similarly, Rossi et al. (2012) performed the investigations on a detached house in two different climates: the temperate maritime climate of Brussels (Belgium) and the subarctic climate of Lulea (Sweden), with the inclusion of OE for space cooling and heating but excluded the MEP and site features. On the other hand, Ramesh et al. (2012b) studied a single-family house with different wall materials and varying insulation thickness in the tropical climate of Hyderabad (India) using energy simulation tools but neglected the site features and the MEP services. Whereas the current study has been conducted on a high-rise residential building project in the composite climate of NCR (India) with a wider system boundary, including MEP and site features.

It is to be noted that, unlike all the above studies that computed the OE through energy simulation tools, the current study estimated the OE with actual energy consumption measurements taken from the energy meters and is expected to be comparatively higher in accuracy of results (Yoshino et al., 2017).

5.4.2 Way forward

MEP services accounted for a large proportion (more than 50%) of the total OE of all sub-systems. The selection of MEP equipment during initial construction is made by the developer and is beyond the control of owners/occupants. Therefore, the occupants/resident associations would need to utilise the opportunity by selecting MEP equipment of higher energy efficiency rating at the time of replacements to reduce operating energy consumption during the remainder life span of the building project.

Within the operation stage, REE consumption is found to be nearly 20% of the total energy demand during the operation stage **(Figure 5.4)**. Therefore, timely repair and maintenance to prolong the service life of building materials and components can help reduce REE consumption.

It is also observed that the relative proportion of operating energy of sub-systems with lower initial EE (e.g., External water supply, Sewage treatment plant, HVAC) is generally found to be higher than that of sub-systems with higher initial EE (e.g., Residential towers, Vehicle parking) **(Figure 5.5)**. This emphasises the need to select electro-mechanical equipment with higher energy efficiency ratings, such as 4-Star and 5-Star, during initial construction to reduce the operating energy demand in the occupation stage (BEE, 2015).

Buildings have a long life span of 50 to 100 years. Most buildings that would comprise the building stock for the next 30 to 40 years or more have already been built as conventional buildings, which consume more energy than low-energy buildings. Therefore, a country-specific action plan needs to be formulated for cost-effective energy efficiency measures in a phased manner to meet national commitments towards the UN SDGs. The energy efficiency measures on existing build stock may include improvement and enforcement of building energy codes, retrofitting of the building envelope, and use of high-efficiency products and equipment.

In practice, the frequency of repair, maintenance or replacements may be influenced by various constraints, e.g., technological trends, material degradation due to environmental exposure, nature of usage, aesthetic reasons, and convenience of the owners or occupants. However, the decisions on retrofitting of buildings would have to be taken based on cost-benefit analysis from economic, environmental and social considerations, which may require strong motivation of the stakeholders induced by legislation duly supported through incentives and affordable financing instruments.

5.5 SUMMARY

This chapter aimed to study the energy demand of the building project during the occupation stage. Data was collected using field measurement or site survey methods. Energy meter readings and details of manpower deployment and expenditure on operation and maintenance of the building project sub-systems were obtained from the facility management records, and data verification was carried out by technical discussion with key personnel during the on-site visits. In the energy analysis, energy consumed on replacements, repair and maintenance (recurring embodied energy), and energy consumption for the operation of sub-systems (operating energy) was computed using simple arithmetic. MEP sub-systems consumed the highest proportion of recurring embodied energy (REE) amongst all sub-systems due to the higher frequency of replacements and maintenance requirements. Similarly, MEP sub-systems also consumed the highest proportion of operating energy (OE), mainly due to the high power requirements of HVAC sub-system for space heating and cooling. The chapter concludes while suggesting some methods for reduction in the REE and OE, such as: a) the need for selecting durable electro-mechanical equipment during initial construction and regular maintenance to avoid frequent replacements; b) selecting electro-mechanical equipment of high-energy efficiency rating during initial construction and subsequent replacements; and c) revision of energy codes to bring a higher plinth area for mandatory enforcement of energy conservation measures on the new and existing building stock.

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CHAPTER 6: ENERGY ANALYSIS OF POST OCCUPATION STAGE

6.1 INTRODUCTION

Buildings may be demolished due to technical reasons such as normal degradation of structural soundness at the end of life span or damage caused by natural calamities, faulty design or execution, use of inferior quality building material (Ghaemi & Amidpour, 2019), lack of periodic maintenance, and low building energy efficiency as mandated by revision of building energy codes. Buildings may also be demolished due to non-technical reasons, such as appreciation in land value, change in functional requirement (Cobbinah et al., 2019), and violation of building bye-laws. Also, building demolition is traditionally perceived as a necessary evil due to the large amount of energy consumed and problems associated with the management of demolition waste (Kabirifar et al., 2020b), apart from the inherent issues of dust and noise in the neighbourhood.

Building demolition involves the use of demolition energy, which may be defined as the direct energy and indirect embodied energy required for deconstruction, demolition, and transportation for reuse, recycling or disposal of demolition waste. (Atmaca & Atmaca, 2015; Vitale et al., 2017). Energy consumption is invariably associated with the emission of greenhouse gases, which impact the environment (Vossberg et al., 2014) and society at large. Significant amount of embodied energy can be recovered or saved through recycling and reuse of recovered material in new construction, thus reducing the requirement of energy spent in mining of natural resources, their transportation and processing as found in a study by Indian Bureau of Mines (IBM, 2017). Therefore, reduction in energy consumption for building demolition and increasing the recovery of energy by reuse or recycling of demolition waste becomes a societal (Kabirifar et al., 2020a) obligation on the part of stakeholders.

Growth in population and scarcity of land, especially in urban areas, have led to high-rise construction wherein building demolition requires the use of explosives since mechanical demolition is not feasible. However, studies on demolition energy estimation of high-rise buildings using explosives have been limited in number. Moreover, most of the past studies on building demolition focused on the analysis of waste generation, management of construction and demolition (C&D) waste, and environmental impact of C&D waste without exploring the energy requirement for demolition of buildings (Faleschini et al., 2016; Islam et al., 2019). In addition, a significant proportion of researchers, including that by Crawford (2014) estimated the demolition energy of buildings based on previous studies instead of primary data, thus raising concern about the reliability of these studies.

Therefore, this chapter is aimed to estimate the demolition energy requirement of a high-rise residential project during the post-occupation stage while addressing the above shortcomings. The system boundary for the energy analysis includes all sub-stages of the building project's end-of-life stage, viz., demolition, transportation, reuse/recycling, and disposal. Similarly, the system boundary also considers all sub-systems of the building project, i.e., residential towers, parking, MEP services and site features. Primary data has been collected through semi-structured interviews during site visits of actual demolition of similar high-rise buildings using controlled explosion. Data analysis has been carried out using input-output analysis (Zhu et al., 2020) of the Indian economic sectors (Singh & Saluja, 2018).

6.2 MATERIAL AND METHODS

6.2.1 Case description

A large modern housing complex situated in the National Capital Region (NCR) of India was selected as the case study to gain insights to answer the research question. This case study project comprises high-rise residential towers with heights of up to 20 storeys and a total built-up area of about 160,000 m^2. The residential towers are reinforced cement concrete (RCC) frame structures with brick wall infills, wooden doors, unplasticised polyvinyl chloride (UPVC) frame windows with single glazing and marble, laminated wooden and ceramic tile floors. The building complex, newly constructed in 2019, is considered for prospective demolition after its useful life of 50 years.

6.2.2 Data collection

To facilitate the data collection and analysis, the system boundary for this project has been fixed, as shown in **Figure 6.1**. Further details of the sub-systems considered for this project based on the functional criteria are already shown previously in **Table 3.1** in Chapter 3. Data on building project was collected in terms of contract documents, building drawings and purchase orders from the developer and project management consultant.

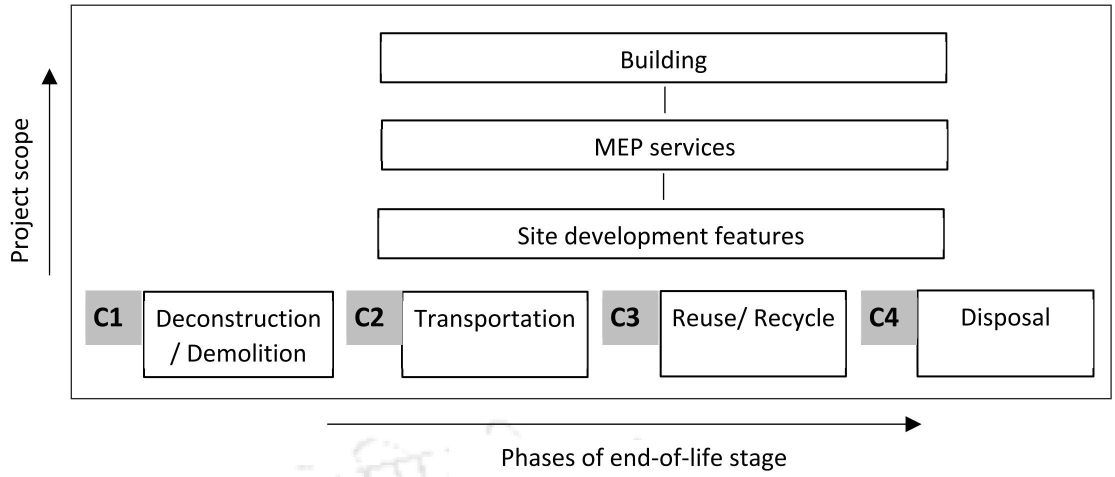


Figure 6.1 System boundaries selected for case-study research

The rates for the dismantling of all removeable items (e.g., doors and windows), brick wall infills, items used in external services and specialised items (e.g., elevators and firefighting equipment) were obtained from various sources, such as the CPWD (2013), service engineers, senior working professionals, experienced contractors and original equipment manufacturers (OEMs). Data on the cost/energy consumption of the demolition of high-rise residential buildings using controlled explosion is not available in the public domain due to the technical and commercial confidentiality maintained by the few specialised agencies (Kang et al., 2022) that work in the area of controlled explosion (commonly termed 'implosion'). Therefore, the rates for the demolition of RCC frame structures using controlled explosion were determined based on cost estimations from the actual demolition of two towers, namely Tower A and Tower B, of another project in the same region. A similar approach was previously adopted by Scheuer et al. (2003) and Srinivasan et al. (2014).

Estimation of cost of demolition using controlled explosion

Tower A and Tower B were 32 storeys and 29 storeys high, respectively, with a total built-up area of approximately 70,000 m^2, and were ordered for demolition due to violation of local by-laws. These towers were demolished using hybrid demolition consisting of deconstruction, mechanical demolition, and controlled explosion. Explosive design was carried out by an explosive consultant based on the type of building structure, strength of concrete, size of steel reinforcements and location of neighbouring properties.

Administrative clearances were obtained from various government authorities. Deconstruction of the building was undertaken in a top-down sequence to dismantle MEP items and demolition of brick wall infills through the employment of labour, tools, plants and machinery.

The buildings were prepared for controlled explosion in the following sequence:

i. Each shear wall was converted into two pseudo columns by cutting and removing the middle portion of the shear wall to reduce lateral resistance to collapse of the structure **(Figure 6.2**).
ii. Bore holes of 32 to 35 mm diameter were drilled in the columns and pseudo columns using diamond core cutting machines **(Figure 6.2**) for the placement of explosive charges.
iii. Affected columns and pseudo columns were wrapped with a chain link fence and geotextile fibre to prevent the spread of debris during the explosion.
iv. Sand/debris cushioning was provided in lower basement and a ditch was created around the building to minimise the ground vibration due to falling debris.

A test blast was also conducted on one of the higher floors to check the efficacy of the explosive design. A final inspection was carried out just before firing the explosives, and the charges were fired from the control room located outside the exclusion zone. Both towers came down in a water cascade pattern within 15 seconds.

The cost estimation for the demolition of the RCC-framed structures of Tower A and Tower B by controlled explosion was carried out based on cost elements, as shown in **Table 6.1.** The cost of secondary demolition has been taken as 30% of the cost of primary demolition of RCC by mechanical methods, based on CPWD Schedule of (CPWD, 2013) and discussion with experts. The CPWD Delhi Schedule of Rates are revised periodically, can be fairly relied upon and have also been used by many researchers e.g., Bansal et al. (2021), Mastrucci and Rao (2019) and Vyas and Jha (2017) among others. The administrative cost amounted to approximately 10% of the total cost of demolition.

(a) Drilling of bore holes in shear walls using diamond core cutting machine

(b) A column after drilling bore holes

(c) Wrapping of columns with chain link fence and geo-textile fabric

(d) Residential towers after charging with explosives, just before demolition

(e) Debris of residential towers few minutes after demolition by controlled explosion

Figure 6.2 Actual site photographs of Tower A and Tower B demolition by controlled explosion

Table 6.1 Cost elements considered for cost estimation of controlled explosion

Type of cost	Cost elements considered
Administrative cost	Cost of clearances from Government agencies including licences for explosive transport and usage
	Cost of technical consultant to assess structural safety of building under demolition during preparatory work for controlled explosion
	Cost of pre and post explosion structural audit of neighbouring properties, monitoring of essential parameters related to actual controlled explosion (e.g., ground vibration, air over pressure, noise level)
	Cost of site safety measures-CCTV cameras, curtain wall
	Cost of office establishment-project office and office staff
	Cost of third-party insurance against damage/injury to personnel and properties during demolition work
	Management cost- chief executive officer, project manager, project coordinator
Cost of plant & machinery	Diamond core cutting machine for drilling of bore holes for explosive placement
	Lift and hoist for labour & material
	Operation of DG sets-fuel cost, capital cost
	Cost of dust control system during preparation of building for explosion and during actual explosion
Labour and technical supervision cost	Plant and machinery operators, skilled and unskilled labour, security staff and site engineers
Cost of explosive related work	Cost of explosive consultant for design and execution of controlled explosion (supervision, charging, and firing of explosives)
	Cost of explosives and explosive accessory
Cost of expendables	Chain link fence and geo-textile fabric for wrapping of blast columns, personal protective equipment- safety gear, safety shoes and helmets
Cost of secondary demolition after controlled explosion	Breaking/pulverisation of large size concrete pieces into small pieces for ease of segregation, loading and transportation from demolition site to waste processing plant
Contractor's profit	The contractor's profit was considered as 10% based on discussion with demolition contractor

6.2.3 Demolition energy estimation

Three main approaches to estimating the embodied energy of the demolition stage using inventory analysis are input-output analysis, process analysis and hybrid analysis (Stephan et al., 2019; Suh et al., 2004). The strengths and shortcomings of these three approaches have been reviewed by Crawford and Treloar (2005). Although input-output analysis has been reported to have limitations due to assumptions of aggregation and homogeneity of all processes with in a sector, it has the advantages of encompassing complete system boundaries (Crawford & Treloar, 2005) and affording geographical representativeness (Dixit et al., 2012). In the present study, an input-output analysis approach as suggested by Zhang and Wang (2016) was adopted to answer the research question, as the process data for demolition work was not available.

In stage 1 of the analysis, the quantity of demolition waste generated from the demolition of the case study building project was estimated. Methodologies for the quantification of demolition waste were earlier reviewed by Wu et al. (2014). Six categories of existing methods were identified: the variable modelling method, site visit method, waste generation rate method, lifetime analysis method, classification system accumulation method and other miscellaneous methods. Material flow analysis (Cochran & Townsend, 2010) has been found to be the main approach in all these methods (Central Pollution Control Board, 2017). For the current study, the lifetime analysis method (Poon, 1997) was employed, utilising material flow analysis during the construction stage, with modifications to account for construction wastages and the efficiency of the sorting process of demolition waste.

A wastage rate of 1–10% for building materials during the construction stage has been reported by Chau et al. (2007), and (Hao et al., 2008). For the current study, an average wastage rate of 5% was taken to cater for improvements in construction methods, for instance, the use of ready-mix concrete (RMC), the use of modern construction machinery such as material hoisting cranes, the use of steel shuttering, and improvements in supply chain infrastructure (e.g., vendor and transportation networks). To elucidate further, concrete constitutes nearly 75% of the total weight of all construction materials. In modern construction, the wastage of concrete has been reduced considerably due to the use of RMC, which is directly pumped to the site. Similarly, the use of improved materials, such as steel for scaffolding and shuttering (Chen et al., 2002) in place of timber; increased efficiency of on-site material management (Liu et al., 2020), including adequate storage facilities; avoidance of rework (Asadi et al., 2021) by better design (Wang et al., 2014) and site supervision; and improved utilisation of resources through the employment of project management consultants have led to a considerable reduction in the proportion of construction waste. Additionally, the recovery rate (sort level) for all reusable or recyclable materials after demolition was considered to be 95%, based on

Thormark (2002), and the balance of 5% of all materials constituted the mixed debris consigned to landfill.

In stage 2 of the analysis, the net cost of demolition incurred for each sub-system was computed. During the end-of-life phase, resources (energy and cost) are consumed during the demolition of the building project for the use of labour, plant and machinery, power consumption and the cost of explosives and accessories in case of a controlled explosion, as well as administrative costs for government approvals, project management and risk insurance. Thereafter, resources are expended on the transportation of demolition waste to recycling agents/recycling facilities, waste processing plants or landfills, depending on the type and method selected for the disposal of waste materials. Finally, resources are consumed for the processing of waste, such as concrete, into recycled products, such as recycled aggregates, concrete blocks and pavement blocks. On the other hand, resources are recovered from the sale of scrap for reuse or recycling. The net cost incurred during the demolition process is estimated based on Equation (Eq) (6.1):

$$C_{net} = \sum_{i=1}^{n} C_{net(i)} = \sum_{i=1}^{n} [\, C_{scrap(i)} - C_{dem(i)} - C_{trans(i)} + C_{proc(i)} \,] \qquad (6.1)$$

Where:

$C_{net(i)}$, $C_{scrap(i)}$, $C_{dem(i)}$, $C_{trans(i)}$, and $C_{proc(i)}$ denote the net cost of demolition, the cost recovered from the sale of scrap, the cost of demolition activity, the cost of transportation for reuse/recycle/landfill and the cost of processing demolition waste for each sub-system 'i' respectively.

C_{net} denotes the overall cost incurred during the whole building project's demolition.

In stage 3 of the analysis, the embodied energy intensity of Indian construction sector was computed using Leontief's Inverse Matrix equation on the Input-Output Table 2013-14 for Indian economy (Singh & Saluja, 2018). The calculations have been carried out using the 130 x 130 commodity-commodity matrix table of the Input-Output Table 2013-14 because it has been reported to be more suitable than industry x industry table, in most applications (MoSPI, 2012). Details of computation have already been covered in Section 4.2.5 of Chapter 4: Pre-occupation stage.

The total (direct and indirect) energy intensity of the construction sector (EI_{constr}) is thus estimated as 37.26 GJ/Rs Lakhs of output of construction sector.

In stage 4, the demolition energy incurred during the demolition of each sub-system was computed using Eq (6.2):

$$DE = \sum_{i=1}^{n} DE_{(i)} = \sum_{i=1}^{n} [\, C_{net(i)} \text{ X } EI_{constr} \,] \tag{6.2}$$

Where:

$DE_{(i)}$ and $C_{net(i)}$ are demolition energy and net cost of demolition of each sub-system 'i' respectively,

EI_{constr} is the energy intensity of the construction sector, and

DE is the demolition energy requirement of the whole building project.

6.3 RESULTS

6.3.1 Estimation of demolition waste generated.

The quantity of demolition waste generated was computed based on contract documents on building construction, Indian Standard Codes, OEMs technical specifications, and assessments based on inputs from experts. The proportion of waste generated by the sub-systems along with the total waste, is shown in **Figure 6.3.**

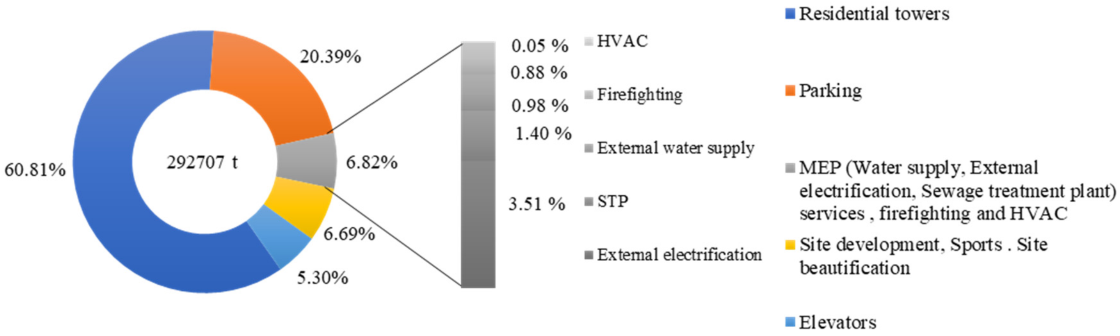


Figure 6.3 Proportion of waste generated by the sub-systems

The overall composition of demolition waste generated during the entire building project demolition including MEP and site features sub-systems is shown in **Figure 6.4**. It is observed that concrete and non-concrete inert waste accounts for nearly 95.6% of the total demolition waste generated while metals, PVC and timber scrap collectively make the up the remaining 4.4%.

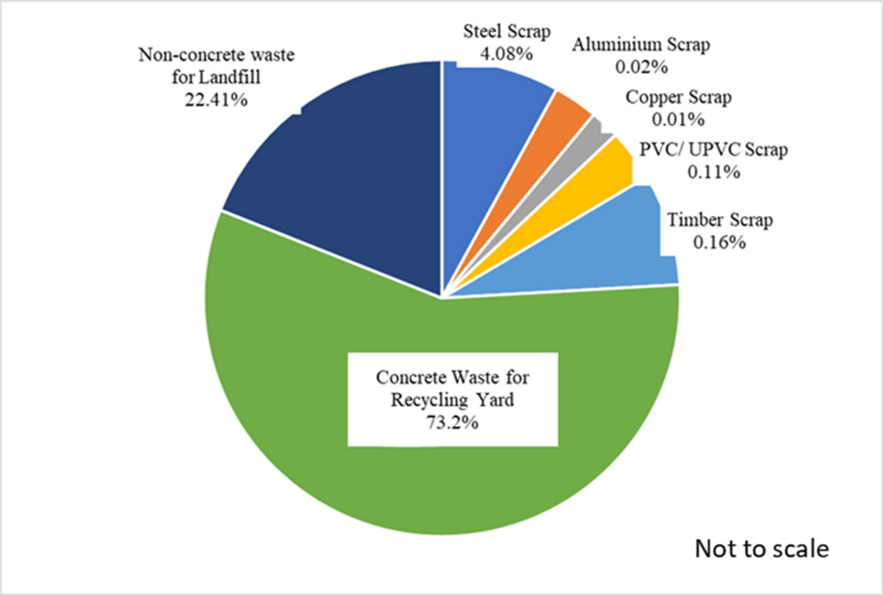


Figure 6.4 Composition of demolition waste generated in the current study

6.3.2 Estimation of demolition energy of sub-systems

The cost/unit for dismantling/demolition of some important materials is shown in **Table 6.2**, and the conversion factors used for the materials' volume-to-mass conversion are given in **Table 6.3.**

At present, two private firms, IL&FS Environmental Infrastructure & Services Limited (IEISL, 2022) and Ramky Enviro Engineers Ltd (REEL, 2022), are the agencies approved by urban local bodies (ULBs) in the National Capital Region for recycling concrete in C&D waste. The agencies charge Rs 8/ton/km for concrete waste collection, including loading and transportation from the waste generation site to the waste processing plant, and an additional Rs 165/ton as waste processing fees. The transportation distance from the demolition site to the waste processing plant or recycling yard is approximately 25 km. For ease of computation, the transport distance from demolition site to scrap vendor and landfill site was also assumed to be 25 km. At present, scrap vendors and landfill sites are available within 25 km; however, as the city grows, these distances are likely to increase further. Moreover, the selection of a scrap vendor would depend on factors such as the quoted price of scrap material, the storage space available and the cost of transportation. Data on rates of scrap material were obtained from websites such as Indiamart (2022) and Recycleinme (2022) and were duly corroborated by demolition contractors and scrap vendors **(Table 6.4**).

Table 6.2 Cost of dismantling/demolition of materials

Item	**Unit**	**Rates for dismantling/ demolition (Rs/Unit)**	**Remarks**
RCC by controlled explosion	m^3	2549.70	Includes primary and secondary demolition
RCC by mechanical demolition	m^3	411.87	Only secondary demolition
PCC (M 7.5 or below)	m^3	149.15	Only secondary demolition
PCC (above M 7.5)	m^3	241.91	Only secondary demolition
Brickwork 230 mm	m^3	681.00	
Dressed stone work in cement mortar	m^3	950.60	
Laminated timber in flooring	m^2	35.00	
Doors and windows shutters including frames			
(a) Area 3 sq. metres and below	Each	127.80	
(b) Area beyond 3 sq. metres	Each	175.50	
Aluminium doors	Nos	175.50	
Mild Steel structural works	Ton	6236.00	
Kitchen sink stainless steel	Nos	174.74	
Pumps-various sizes 2-15 HP	Each	500.00	
Dismantling G.I. pipes (external work)			
(a) 15 mm to 40 mm nominal bore	m	52.60	
(b) Above 40 mm nominal bore	m	59.70	
Transformers	Each	20000.00	
Overhead lines comprising of copper/ aluminium overhead conductor	Ton	2230.00	

Sources: CPWD (2013), demolition contractors and experts

Table 6.3 Conversion factors for building material

Item	**Unit**	**Weight**
Full brickwork	kg/m^3	2200
Cement mortar	kg/m^3	2040
Plain cement concrete (PCC)	kg/m^3	2320
Reinforced cement concrete (RCC)	kg/m^3	2450
Ceramic tiles	kg/m^3	2200
Wooden laminated flooring	kg/m^3	900
Medium density fibreboard (MDF)	kg/m^3	750
Gypboard	kg/m^3	670
Marble stone	kg/m^3	2700
Granite stone	kg/m^3	2640
Sand stone	kg/m^3	2240
Wood	kg/m^3	640
Glass sheet	kg/m^3	2600

Source: BIS (1987)

Table 6.4 Rates of scrap material used in current study

Item	**Unit**	**Rates (Rs/unit)**
Steel / Cast iron	kg	30
Aluminium	kg	90
Copper	kg	500
UPVC, HDPE, PVC	kg	8
Laminated timber	kg	10
Medium density fibreboard (MDF)	kg	5
Electronic waste	kg	10

Sources: Indiamart (2022), Recycleinme (2022), scrap vendors, demolition contractors

The total demolition energy expended in the dismantling and demolition of the building components, transportation for disposal of demolition waste and processing of waste, along with the share of each sub-system, is shown in **Table 6.5** and **Figure 6.5**. Similarly, the total demolition energy recovered, along with the share of each sub-system on account of reuse/recycling of scrap material, is shown in **Table 6.6** and **Figure 6.6.** The net demolition energy incurred (shown as -ve) or recovered (shown as +ve) by each sub-system during the complete demolition process calculated using Eq (6.2) (viz., energy expended on dismantling/demolition of building components, transportation and processing of demolition waste, and energy recovered from recycling of scrap), is shown in **Figure 6.7**.

Table 6.5 Demolition energy consumed by sub-systems

Sub-system	**Cost of dismantling /demolition (C_{dem}) (Rs Lakhs)**	**Cost of transportation (C_{trans}) (Rs Lakhs)**	**Cost of processing waste (C_{proc}) (Rs Lakhs)**	**Total cost of demolition (C_{total}) (Rs Lakhs)**	**Demolition energy consumed (GJ)**	**Demolition energy consumed (%)**
(A)	(B)	(C)	(D)	C_{total} =(B+C+D)	C_{total}*EI_{constr}	
Residential towers	1279.71	209.13	109.65	1598.49	59559.90	57.19
External water supply	28.87	3.37	2.45	34.69	1292.63	1.24
External electrification	74.51	12.08	5.66	92.24	3437.02	3.30
Sewage treatment plant	34.91	4.81	3.83	43.55	1622.78	1.56
Site development features	66.80	18.20	6.09	91.08	3393.68	3.26
Parking	500.72	70.12	64.36	635.20	23667.39	22.73
HVAC	34.02	0.16	0.00	34.19	1273.78	1.22
Elevators	120.87	18.24	8.50	147.61	5499.82	5.28
Firefighting	75.59	3.02	1.33	79.94	2978.44	2.86
Sports	17.85	2.48	1.65	21.98	818.91	0.79
Site beautification	13.16	2.32	0.57	16.05	598.14	0.57
Total	2247.01	343.92	204.09	2795.02	104142.49	100.00

EI_{constr} - Energy intensity of Construction Sector computed from I-O Tables 2013-14 of Indian economic sectors=37.26 GJ/Rs Lakhs

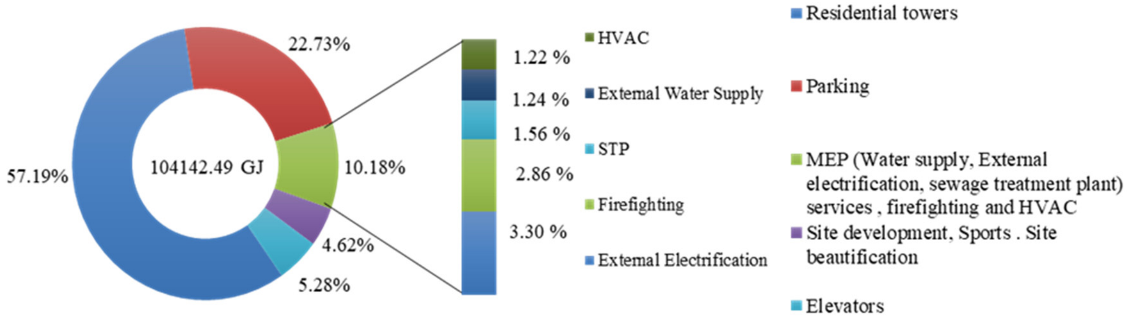


Figure 6.5 Demolition energy consumed by sub-systems

Table 6.6 Demolition energy recovered by sub-systems

Sub-system	**Cost recovered from Sale of scrap (Cscrap) (Rs Lakhs)**	**Demolition energy recovered from sale of scrap [C_{scrap} X EI_{constr}] (GJ)**	**Demolition energy recovered from sale of scrap (%)**
Residential towers	2362.82	88038.85	62.84
External water Supply	31.32	1167.07	0.83
External electrification	283.05	10546.45	7.53
Sewage treatment Plant	32.61	1215.02	0.87
Site development features	70.55	2628.74	1.88
Parking	430.00	16021.86	11.44
HVAC	153.21	5708.66	4.08
Elevators	217.04	8086.86	5.77
Firefighting	141.66	5278.33	3.77
Sports	21.15	787.98	0.56
Site beautification	16.37	609.84	0.44
Total	3759.79	140089.64	100.00

EI_{constr}-Energy intensity of Construction Sector computed from I-O Tables 2013-14 of Indian economic sectors=37.26 GJ/Rs Lakhs

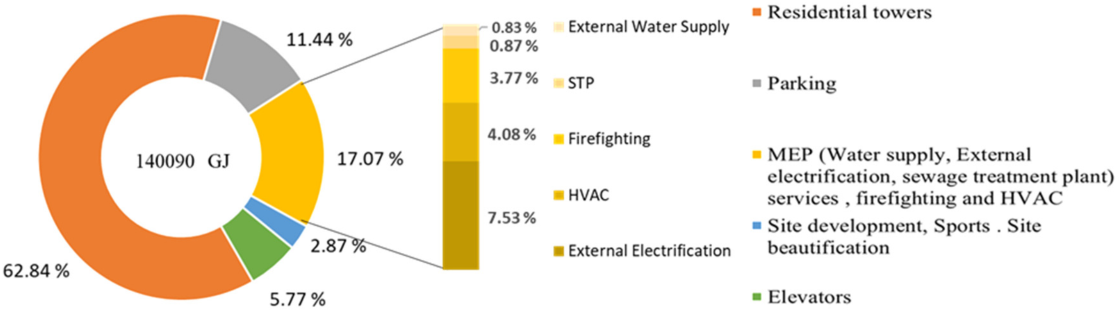


Figure 6.6 Demolition energy recovered by sub-systems from recycling of scrap

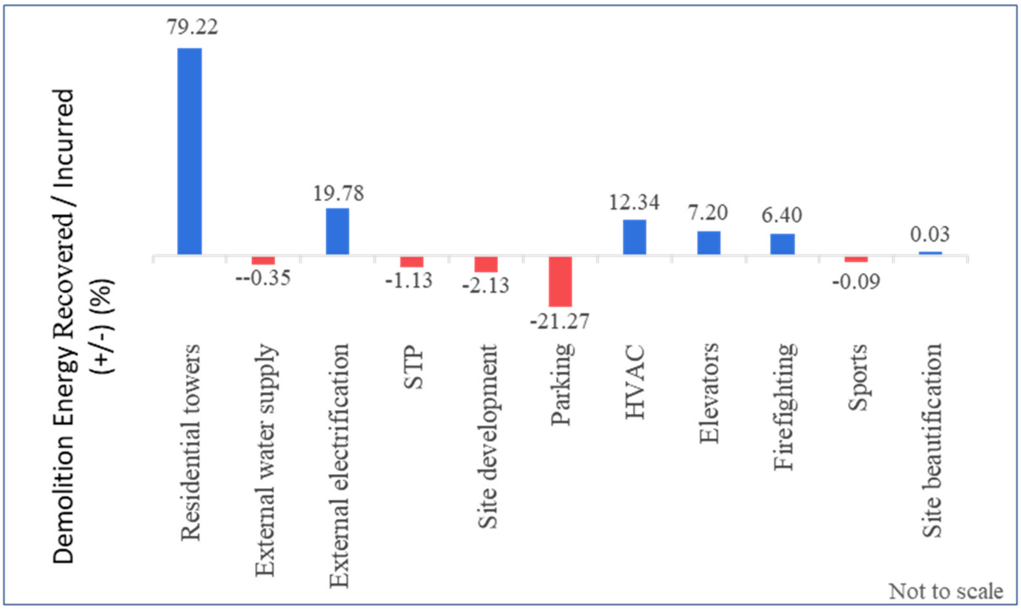


Figure 6.7 Net demolition energy recovered or incurred by sub-systems

It is observed that sub-systems, such as external water supply, sewage treatment plant, site development, parking and sports facilities, incurred negative demolition energy (which implies energy expended), whereas all other sub-systems incurred positive demolition energy (which implies energy recovered) mainly due to positive net cost recovery on the sale of scrap material **(Figure 6.7)**. The parking sub-system consumed the highest net demolition energy (-21.27%) due to the higher amount of demolition energy required for the demolition of concrete, but the lower amount of energy recovered from recycling steel, as the parking sub-system is lightly reinforced compared to the residential tower sub-system.

Overall, the building demolition resulted in savings in demolition energy, or a reduction in embodied energy during the building life cycle, amounting to approximately 36,000 GJ. The share of energy consumption from demolition activities (excluding energy recovered from the sale of scrap) is shown in **Figure 6.8.**

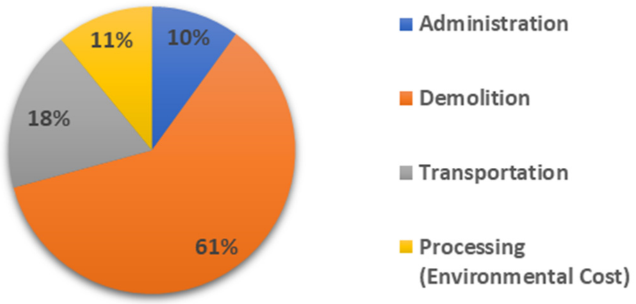


Figure 6.8 Share of energy consumption of demolition activities

6.4 DISCUSSION

6.4.1 Comparison of categorisation of demolition waste

The categories of demolition waste generated in the current study are compared with those of other Indian and international studies in **Table 6.7**. The demolition waste in studies conducted by the Technology Information Forecasting and Assessment Council (TIFAC, 2001) and Coimbatore City Municipal Corporation (CCMC, 2015) pertains to buildings of around 50 years old or more, whereas this case study pertains to a new building constructed in 2019. The variation in the proportions of concrete and brick masonry between the TIFAC (2001) and CCMC (2015) studies and the current study is due mainly to changes in construction technology and the shift from load-bearing walls of brick masonry to RCC-framed structures. The variation in the proportions of concrete and brick masonry between Blengini (2009) and the current study appears to be due to the use of concrete shear walls and a small proportion of brick walls by Blengini (2009) in place of only brick wall construction with no shear walls in the current study. A reduction in the share of timber in modern high-rise construction (in this study) compared to the TIFAC

(2001) and CCMC (2015) studies is due to the use of RCC frame construction and UPVC windows in place of timber in structural members, as well as window frames and shutters in older low-rise buildings, due to structural safety and environmental concerns. The proportion of demolition waste in this study is in close agreement with Cha et al. (2020), with a combined share of concrete and brick masonry of nearly 91% in both cases. The higher percentage of concrete and metals and a lower percentage of brick masonry in this study can be attributed to the presence of an RCC basement with negligible brickwork and a high-rise building structure, as compared to low-rise stand-alone buildings without basements in Cha et al. (2020). The above argument regarding the requirement of a higher quantity of building materials in the structural members of taller buildings compared to that of low-rise buildings seems justified in light of similar results reported by other studies, such as those of Gunel and Ilgin (2007) and Foraboschi et al. (2014).

Table 6.7 Comparison of categorisation of demolition waste

Type of waste	TIFAC (2001) (%)	CCMC (2015) (%)	Blengini (2009) (%)	Cha et al. (2020) (%)	Current Study (%)
Concrete	23.00	23.00	82.55	67.22#	73.20
Brick masonry	31.00	19.00	4.33	24.40	17.32
Metals	5.00	4.00	3.63	2.27	4.12
Timber	2.00	2.00	0.11	1.31	0.16
Others (soil, sand, gravel etc)	39.00	52.00	9.38	4.80	5.20
Total	100.00	100.00	100.00	100.00	100.00

- includes concrete blocks

6.4.2 Comparison of waste generation rate

The waste generation rate across nations has been reported to vary from about 915 kg/m^2 (Florida, USA) to 1635 kg/m^2 (Spain) as reviewed by Ram and Kalidindi (2017) and is not being elaborated any further.

The rate of demolition waste generated during the current study was approximately 1,715 kg/m^2 of built-up area, excluding scrap material, such as metals, timber and PVC. This is higher than the waste generation rate of 1,430 kg/m^2 found by Ram and Kalidindi (2017). The reasons for this variation appear to be the approximations used by their study and the use of statistical methods. Moreover, the study by Ram and Kalidindi (2017) was conducted on low-rise stand-alone houses at the city scale, as compared to the current study, which was performed on high-rise residential buildings at the project scale. Another possible reason could be the loss of demolition waste in previous studies due to illegal dumping to save disposal costs.

However, a similar study on Shenzhen city in South China found waste generation from the demolition of framed residential buildings to be the largest (1,873.74 kg/m^2) among the examined buildings (Wu et al., 2016). The results of the current study on the waste generation rate (1,715 kg/m^2) are in reasonable agreement with the findings of the Chinese study. Moreover, the rate of demolition waste generated and its composition also depend on a number of factors, such as the type of building (e.g. residential or non-residential), method of demolition (deconstruction, mechanical or controlled explosion), geographical location (climate, earthquake zone), type of construction material used (e.g. bricks or concrete blocks used for wall infills), method of estimation of waste generation (statistical modelling, past experience versus actual site measurement) and scope of study (project components considered). More studies at the project scale are required to validate the findings of studies done at the regional or city scale.

6.4.3 Contribution of building project components

In the current study, building-related sub-systems (residential tower and parking sub-systems) produced the highest proportion of demolition waste (81.20%). Though non-building sub-systems (MEP services, firefighting, HVAC, site development, sports facilities, and site beautification) generated 18.80% of total demolition waste and consumed approximately 20% of the total demolition energy, they were able to recover a proportionately higher amount of demolition energy (25.72%) from the sale of scrap for recycling, primarily due to the higher metal content (steel, aluminium, copper) in the demolition waste. Therefore, the impact of non-building sub-systems on the results of a demolition project cannot be overlooked any further. The embodied energy of metals is higher than that of other construction materials due to the higher amount of energy consumed in the mining, extraction and processing of the material at the production stage.

Amongst the materials, concrete contributed to the highest proportion (73.20%) of demolition waste and consumed the highest share of demolition energy (84.46%), while steel scrap for recycling enabled the highest proportion of embodied energy recovery

(90.46%). Steel scrap, mainly consisting of reinforcement bars and other structural steel, is sold to scrap dealers or aggregators, who further deliver it to scrap processing centres (recycling plants), where it is recycled through remelting in small-capacity electric arc furnaces (EAF) or induction furnaces (Ministry of Steel, 2019). Recycling steel scrap is beneficial, as recycling one tonne of steel scrap results in savings of about 1.1 tonnes of iron ore, 0.6 tonnes of coking coal and 0.05 tonnes of limestone (Tuck, 2021). Additionally, it decreases direct energy consumption and greenhouse gas emissions by nearly 16–17% and 58%, respectively (Damgaard et al., 2009; Ministry of Steel, 2019).

The net demolition energy recovered during the complete demolition process (from demolition to waste disposal, including energy recovery from scrap material) is estimated to be approximately 36,000 GJ (i.e. 2.70% of the embodied energy consumed during the pre-occupation stage of the building project life cycle computed using input-output analysis) and compares fairly well with the figure of 2.0%, as found by Blengini (2009) in Spain. The variation in the results could be attributed to a) variation in system boundaries, for example, the exclusion of MEP equipment by Blengini (2009), and b) a likely difference in energy intensities in the manufacturing industries of the two nations. Moreover, unlike the on-site construction in this study, the building in Spain was prefabricated.

6.4.4 Limitations in estimations during the post-occupation stage

The estimation of cost and energy incurred during the post-occupation stage has been carried out based on prevailing costs during the year 2013-14. It is assumed that the rates of interest will keep pace with the increase in costs due to inflation and the above estimates on demolition costs and demolition energy will also hold good in future. But this may not happen in actual practice. Therefore, the above factors may cause uncertainty in the results. Nonetheless, any future advancements in methods of demolition will always be focused on reducing the costs and energy for building demolition while the proportion of costs and embodied energy recovery from demolition waste will also continue to increase.

6.4.5 Way forward

At present, the market potential of recycled products from waste processing plants in India is not very high, and government subsidies are desirable to support the waste processing industry. Additionally, though recovered scrap and reusable building materials are sold from demolition sites at prevailing prices, some losses may occur due to the degradation of materials and physical losses in the scrap yard. Moreover, fluctuations in the supply and demand of recovered materials may also induce uncertainty in the prices of materials and the cost recovered during building demolition. These uncertainties must be factored into cost and energy analyses for a building demolition project to remain sustainable. In addition, cost and energy recovery from the reuse and recycling of materials and components can be improved by resorting to design for deconstruction or design for disassembly approach.

Another way to reduce the demolition energy requirement is to encourage the use of on-site recycling and recycled products for redevelopment projects, as onsite recycling reduces the transportation cost of waste material and that of material for the new construction.

The project demolition cost and net demolition energy requirements may be positive (profit) or negative (loss) depending on factors such as a) the type of method used, b) market conditions, and c) the existing policy framework. Thus, to promote the circular economy, state agencies may be required to formulate policies on stakeholder awareness; mandatory use of recycled products, such as recycled aggregate, sand and pavement blocks in new construction; and grant subsidies on tipping fees and waste processing fees until the secondary markets for reusable material mature and waste processing plants become financially viable. The current study assumes a sorting level of 95% for recyclable materials. Therefore, methods such as robotic segregation of demolition waste and design for deconstruction or disassembly (Munaro et al., 2020) may be used to improve the level of segregation and recycling.

Presently, recycling plants accept only concrete debris for recycling, and the waste producer must transport non-concrete debris to designated landfill sites. It is proposed that landfills be redesignated as ‘material banks’ or ‘waste exchanges’, where demolition waste could be accepted without any tipping fee and the cost of the land parcel and operational cost of the material banks could be recovered by selling the waste material for reuse. The material banks could be co-located with concrete recycling plants and geographically dispersed throughout a region to reduce the cost of transportation and operation. The land cost for material banks could be subsidised until their operations become economically sustainable. Material banks could help establish an effective supply chain between stakeholder groups (waste producers and material buyers), thereby reducing the land required for landfills.

6.5 SUMMARY

This chapter was aimed to analyse energy demand of the building project during the post-occupation/demolition stage. The case study building project was taken up for prospective demolition after its life span of 50 years. The system boundaries for this stage included all sub-stages of the end-of-life stage viz., deconstruction/demolition, transportation, reuse/recycle, and the disposal of waste to the landfill. Primary data was collected through semi-structured interviews during site visits of actual demolition of similar high-rise buildings using controlled explosion. The data was analysed using input-output method based on input-output tables of Indian economy sectors. Findings indicate that building related sub-systems (residential tower and parking sub-systems) produced the highest proportion of demolition waste (81%) and also consumed the highest share of demolition energy (74%). On the other hand, non-building sub-systems (MEP services, firefighting, HVAC, site development, sports, and site beautification) generated 18.80% of total demolition waste and consumed approximately 20% of the total demolition energy. The rate of demolition waste generated works out to 1715 kg/m^2 of the built-up area. Concrete contributed to highest proportion of demolition waste and consumed highest share of demolition energy, while recycling of steel scrap enabled highest amount of embodied energy recovery. The chapter concludes by recommending some measures, for reduction in the demolition energy consumption, and increase in amount of energy recovered on reuse/recycling of demolition waste.

CHAPTER 7: ENERGY ANALYSIS DURING THE LIFE CYCLE

7.1 INTRODUCTION

The building sector consumes more than 30% of total final energy consumption globally, out of which residential buildings consume the largest share of about 70% (IEA, 2021b). The growth in the building sector is inevitable due to the projected rise in population and GDP across the globe (Santamouris & Vasilakopoulou, 2021). Though sustained efforts are underway to optimise the energy consumption in the building sector, the total energy demand of the building sector, however, is expected to grow at an annual average rate of 1.15% and rise by 23% between 2021 and 2030 (Det Norske Veritas, 2022). Thus, the only option available to offset the likely increase in the energy and environmental impacts of buildings is to work towards the improvement of energy efficiency in buildings. As buildings consume energy throughout their life cycle, life cycle energy analysis can help identify opportunities for improving the energy performance of buildings.

Life cycle energy is the energy consumed from the project conception phase to the end of the demolition phase of a building (project) life cycle. The majority of the previous studies focused their research on individual stages of the building life cycle, such as the pre-occupation stage or operation stage. However, since the activities performed during one stage have a direct or indirect bearing on one or more stages of the building lifecycle, the energy analysis of various stages of the buildings cannot be performed in isolation (Ma et al., 2017). Instead, the energy and environmental burdens need to be evaluated based on the complete life cycle of the buildings.

The life cycle energy of a building is dependent on many factors such as climate, topography/site conditions, type of construction materials used, method of construction used, occupant behaviour, administration and operation of facilities/services, degree of repair and maintenance, and method of demolition and disposal at the building discard stage. Similarly, the findings of energy analysis of buildings will also depend upon parameters such as the purpose of the study, system boundary selection (Omrany et al., 2021), quality of data used, and method/tool employed for the conduct of energy analysis. Variation in quantitative results due to lack of consistency (Birgisdottir et al., 2017) and standardisation (Yokoyama et al., 2017) on energy and environmental assessment of buildings can lead to the formation of incorrect energy optimisation strategies that may not have the desired effects. Therefore, past studies such as those by (Birgisdottir et al., 2017) and Omrany et al. (2021) have highlighted the need for standardisation of procedures for energy analysis to minimise the variation in results and facilitate better comparability across various studies.

As observed from the review of the literature, energy analysis of high-rise residential buildings has not been adequately covered by earlier studies, especially at the building project scale. Accordingly, this study performed the energy analysis of a high-rise residential building project during the pre-occupation, occupation, and post-occupation stages, as covered in the preceding chapters (Chapters 4, 5 and 6).

The aim of this chapter is *to analyse the overall energy requirements of a high-rise residential building project during its entire life cycle*. The scope of the study includes all components of the building project, such as residential towers, MEP services and site features. The remainder of this chapter covers material and methods, and results, followed by discussion on the life cycle energy analysis of a high-rise residential project.

7.2 MATERIAL AND METHODS

Life cycle energy is the sum of energy incurred during all stages of the life cycle of a building project, from pre-occupation to post-occupation. The Results of this phase are computed based on the findings of previous phases of this study. Thus, no primary data has been acquired during this phase to compute the life cycle energy.

In the absence of an industry-wide standard protocol, past studies mainly depended on using various combinations of inventory analysis, energy simulation tools, and LCA tools to evaluate the life cycle energy performance of buildings. These methods, however, suffer from certain limitations. For example, inventory analysis methods suffer from incompleteness of data (Ristimäki et al., 2013) and non-availability of country-specific embodied energy coefficients (Omar et al., 2014), thereby forcing the researchers to either use data of other countries or make assumptions, which lead to errors in the results of embodied energy analysis during the pre-occupation stage.

On the other hand, energy simulation tools/models such as TRNSYS (Klein et al., 2007), EnergyPlus (Crawley et al., 2000), DOE-2 (Booten et al., 2012), and eQuest (Hirsch, 2023) are data and cost intensive and are generally incapable of accommodating the dynamic factors such as weather and occupant behaviour (Sonta et al., 2018). Results of these tools/models exhibit large performance gaps between the designed/predicted values and actual performance values of energy demand during the operation stage (Van Dronkelaar et al., 2016), and are therefore only suitable for use at the design stage for sizing of HVAC equipment, and evaluation of available design options.

Lastly, LCA tools such as ATHENA Impact Estimator (Athena, 2021), SimaPro (PRé Sustainability, 2021), SimStadt (Nouvel et al., 2015), and Eco-Indicator (Pushkar, 2014), which have their integrated inventory databases, act like a 'black box' and only indicate the cumulative energy demand (CED) of the completed building and do not afford energy analysis at the building sub-system/component level. The LCA tools also have inbuilt discrepancies such as incompleteness of data, geographical and temporal relevance, and varying system boundaries (Guan et al., 2016; Robertson et al., 2012).

Therefore, as discussed earlier, this study has employed inventory analysis method with India specific energy coefficients to estimate embodied energy to avoid errors due to lack of geographical representativeness. Additionally, to obviate the performance gaps between predicted and actual energy demand, this study utilised the actual energy consumption measurements from energy meter records to assess direct energy consumption during the operational stage. The indirect energy consumption on the management of operations, repair and maintenance of the building and services was also computed based on actual records of facility management duly verified during field visits. Similarly, the estimation of energy expended during the end-of-life stage is also based on the actual demolition of a similar building in the same region.

The system boundaries selected for life cycle energy analysis include the complete scope of the building project **(Figure 3.1** of **Chapter 3**) and all stages (and sub-stages) of the building life cycle from sub-stage A0 to sub-stage C4 **(Figure 3.2** of **Chapter 3)**. This minimises the error in energy estimation due to incomplete system boundary selection. The life cycle energy of a building project has been estimated using simple mathematics and is given by Eq (3.5) as discussed in Chapter 3: Research Methodology earlier:

$$\text{LCE} = \text{IEE} + (\text{REE} + \text{OE}) + \text{DE} \tag{3.5}$$

Where, IEE, REE, OE. DE and LCE represent the initial embodied energy, recurring embodied energy, operating energy, demolition energy and life cycle energy, respectively, as computed in Chapters 4, 5 and 6 earlier.

7.3 RESULTS

The stage-wise energy consumed by all sub-systems in terms of absolute values and normalised values are as shown in **Tables 7.1** and **Table 7.2**, respectively.

Table 7.1 Energy consumed by all sub-systems (absolute values)

Sub system	**Stage of life cycle**			
	Pre-occupation A0-A5	**Occupation B1-B6**		**Post-occupation C1-C4**
	IEE (GJ)	**REE (GJ/year)**	**OE (GJ/year)**	**DE (GJ)**
Residential towers	946042.90	16182.34	59270.23	28478.95
External water supply	14166.91	435.47	6489.75	-125.56
External electric supply	131540.73	3039.38	5168.43	7109.43
Sewage treatment plant (STP)	20273.86	683.43	4216.05	-407.76
Vehicle parking	199765.62	1286.99	12531.64	-7645.54
Site development features	62526.61	2009.41	2235.30	-764.94
HVAC	86314.69	9833.37	52319.03	4434.88
Elevators	128130.33	3243.19	6019.72	2587.04
Firefighting	53230.23	967.23	3671.46	2299.89
Sports facilities	31862.32	349.27	2583.15	-30.93
Site beautification features	15103.99	626.67	934.65	11.69
Total	16,88,958.18	38656.75	155439.42	35947.15

Table 7.2 Energy consumed by all sub-systems (normalised values)

Sub system	**Stage of life cycle**			
	Pre-occupation A0-A5	**Occupation B1-B6**		**Post-occupation C1-C4**
	IEE (GJ/m^2)	**REE (GJ/m^2/year)**	**OE (GJ/m^2/year)**	**DE (GJ/m^2)**
Residential towers	5.80	0.10	0.36	0.1745
External water supply	0.09	0.00	0.04	-0.0008
External electric supply	0.81	0.02	0.03	0.0436
Sewage treatment plant (STP)	0.12	0.00	0.03	-0.0025
Vehicle parking	1.22	0.01	0.08	-0.0469
Site development features	0.38	0.01	0.01	-0.0047
HVAC	0.53	0.06	0.32	0.0272
Elevators	0.79	0.02	0.04	0.0159
Firefighting	0.33	0.01	0.02	0.0141
Sports facilities	0.20	0.00	0.02	-0.0002
Site beautification features	0.09	0.00	0.01	0.0001
Total	10.35	0.24	0.95	0.2203

The relative share of energy expended by sub-systems, along with the total energy requirement during all stages of the building life cycle, is depicted in **Figure 7.1**.

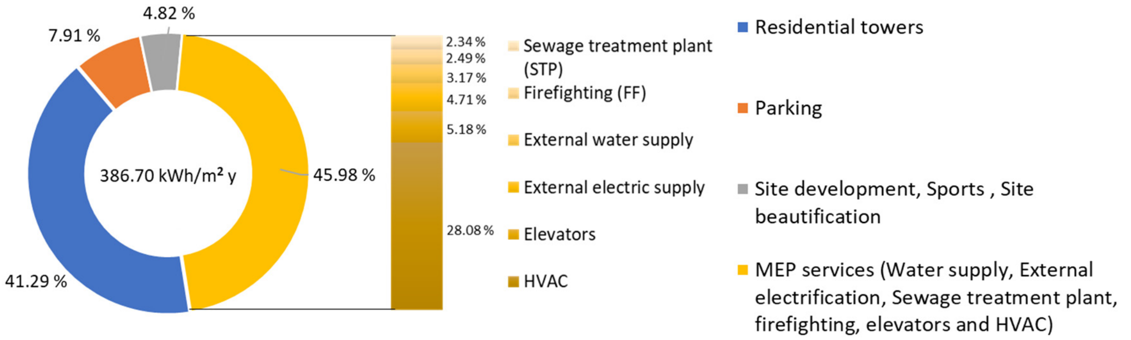
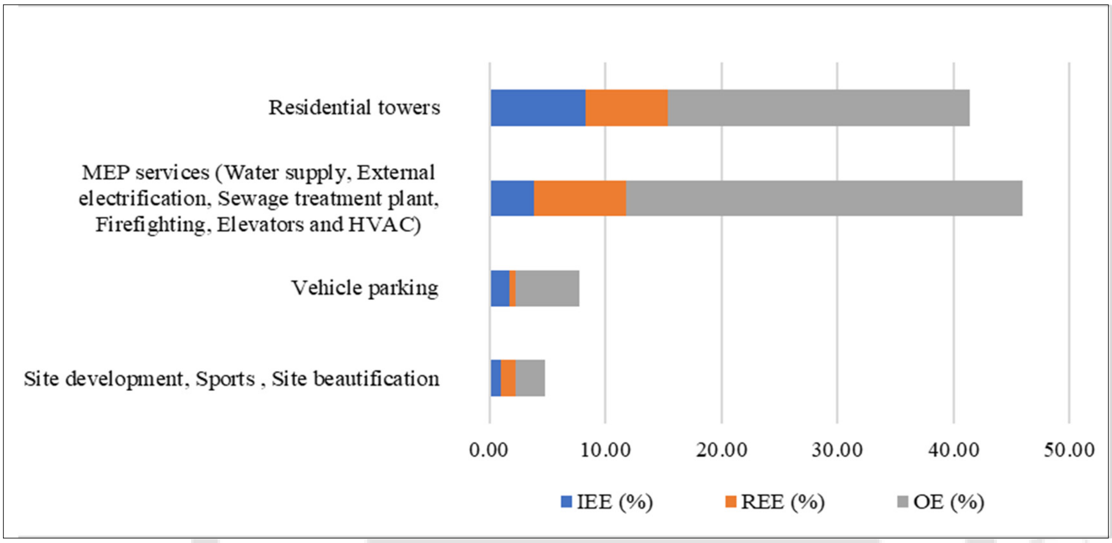


Figure 7.1 Share of all sub-systems in LCE (including recurring EE)

The share of various types of energy consumption by the sub-systems during the entire building project life cycle is placed in **Figure 7.2.** These results show that the initial EE of the residential tower sub-system is higher than that of the MEP sub-systems. On the other hand, MEP sub-systems exhibited a comparatively higher requirement of recurring EE and operating energy than residential tower sub-system. Furthermore, the initial EE, recurring EE and operating energy of vehicle parking and site features sub-systems individually contributed to less than 10% of the total energy incurred by all the sub-systems during the building project life cycle.

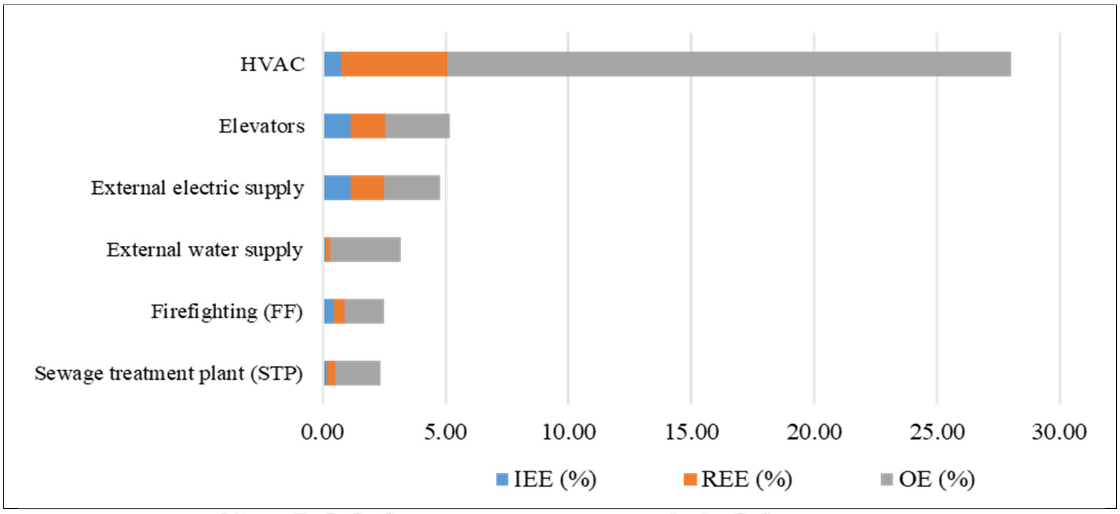


IEE-Initial embodied energy, REE-Recurring embodied energy, OE-Operating energy

Figure 7.2 Share of types of energy consumed during building project life cycle (excluding DE)

The contribution of each sub-systems which comprise MEP services is given in **Figure 7.3.** In the results shown in **Figure 7.2** and **Figure 7.3**, the embodied energy recovered by the sub-systems during the post-occupation stage has been excluded, being a very small proportion of the total LCE.

The total life cycle energy consumption by all sub-systems during various stages is shown in **Figure 7.4**. In this figure, the energy consumption values shown in the pre-occupation stage include only the initial embodied energy expended by the building project during the pre-design/design phase, raw material extraction, transportation of raw material to the manufacturing industry, manufacturing of construction products, transportation of construction material/products to the construction site, and the energy spent during the actual construction of the building project. On the other hand, values shown against the occupation stage comprise the energy consumption on two different accounts: a) the recurring embodied energy for repair, maintenance and replacement of sub-system components and b) the operating energy required for building project sub-systems.



IEE-Initial embodied energy, REE-Recurring embodied energy, OE-Operating energy

Figure 7.3 Share of types of energy consumed by MEP services during building project life cycle (excluding DE)

Similarly, the values depicted for the post-occupation stage indicate the embodied energy incurred for deconstruction, demolition, transport and disposal of the demolition waste. At the same time, the values shown against the total LCE include the total of the embodied, recurring, and operation energy consumed during all three stages of the building project life cycle.

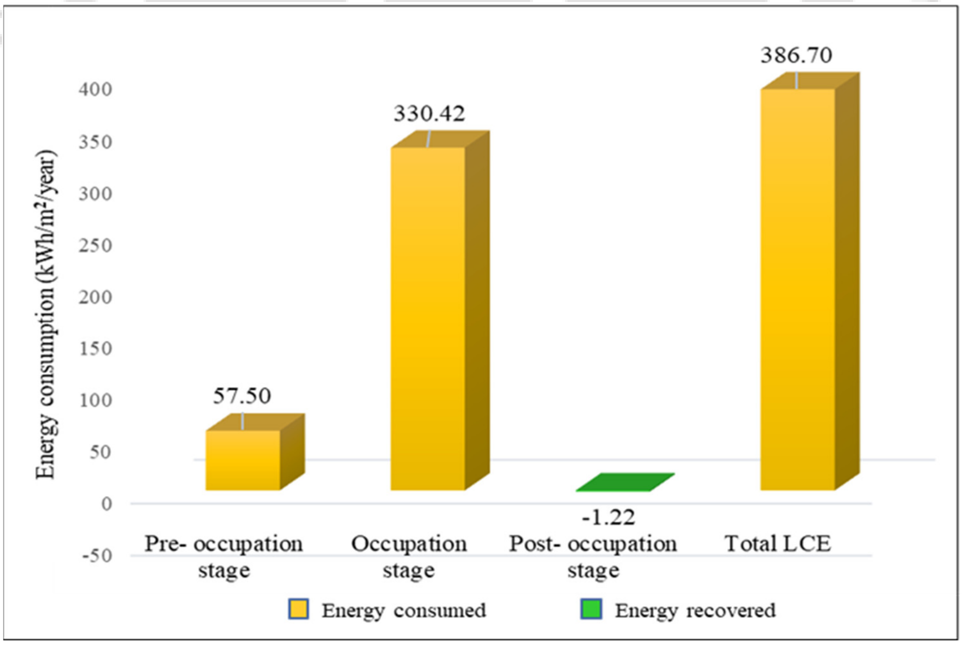


Figure 7.4 Energy consumption of all sub-systems during various stages of the life cycle

7.4 DISCUSSION

It could be observed from the findings of the current case study research that the building related sub-systems (residential tower and parking sub-systems) and non-building sub-systems (MEP services site development, sports, and site beautification sub-systems) consumed 49% and 51% of the total life cycle energy requirement of the building project, respectively. Amongst the MEP services, HVAC contributed to the highest proportion of life cycle energy (28.08%), and sewage treatment plant required the lowest proportion of life cycle energy (2.34%) **(Figure 7.1)**.

In terms of the type of energy consumption, the total embodied energy (IEE + REE-DE) of the building project is found to constitute a large proportion of the life cycle energy, nearly 32% (**Figure 7.2** and **Figure 7.3**). Therefore, approaches to minimise the life cycle energy will have to consider both embodied energy as well as operating energy (Alwan et al., 2021), unlike past studies, which primarily focused on improving the operational energy efficiency of buildings.

Initial EE consumption accounted for approximately 15% of the total life cycle energy of the building project. Embodied energy incurred on escalation of cost due to delay in project completion amounted to nearly 3.5% of the Initial EE. Therefore, strategies such as using low energy intensive material, employing better construction technology and effective project management techniques can help reduce initial EE requirements.

Recurring EE consumption contributed nearly 17% of total LCE over a building life span of 50 years. Therefore, the selection of material during initial construction should be based on the criteria of low maintenance and longer replacement frequencies to minimise the recurring EE for better sustainability. Additionally, these results highlight the importance of quality of construction by employing a well-trained and experienced workforce to obviate the increase in recurring EE on rework/rectification and frequent repairs due to poor workmanship.

Operating energy requirements of all sub-systems are found to be the largest proportion (about 68%) of total life cycle energy burdens. This stresses the necessity for enhanced focus on energy efficiency improvement strategies on MEP services, which contributed to a large share (>50%) of the total operating energy consumption **(Figure 5.3** of **Chapter 5)**. These aspects have been generally ignored or excluded in past studies. In this background, life cycle cost-benefit analysis during the selection of MEP equipment with higher energy efficiency, such as elevators, diesel generator sets, air conditioners, and pumping sets during initial construction and subsequent replacements, assumes greater importance. Additionally, employing professional facility management firms to operate and maintain built assets (large building projects) can also help improve building energy performance.

In terms of stage-wise energy requirements of the building project, the pre-occupation, occupation and post-occupation stages consumed 14.87%, 85.45% and 0.32% of the life cycle energy, respectively **(Figure 7.4)**. The implications of energy consumption during the pre-occupation stage are the same as discussed for initial embodied energy in this section above. The occupation stage (operation stage) accounts for the highest share of life cycle energy burdens (about 85%) but suffers from a dichotomy wherein the interests of the developer are at variance with that of the owners/buyers of property in the building project. For instance, the type and quality of building material and MEP equipment used and the quality of construction is decided by the developer based on his commercial interests, but it has a bearing on the energy demand of the building projects. Thus, the buyers/occupants of the property are not afforded much control over the energy consumption of various sub-systems during the building life span. Therefore, the building occupants must utilise the limited opportunity and opt for building components/equipment with higher energy efficiency during replacements.

The above situation is mainly attributable to the absence of sustainable market demand for low-energy buildings due to a lack of stakeholder awareness of the long-term benefits of savings in operation cost from a life cycle perspective. This establishes the need for undertaking measures to increase stakeholder awareness on commercial and environmental benefits from using energy efficient buildings. The demand for energy efficient buildings can be further enhanced by policy initiatives such as a differential energy tariff based on total monthly power consumption, lower rates of tax on registration of new properties, and annual property tax on a similar line as that of road tax exemption on electric vehicles in some of the Indian states.

The post-occupation or end-of-life (EOL) stage results in the net recovery of energy during the process of demolition, transportation, reuse/recovery and final disposal, unlike all the other stages of the building project life cycle where energy is consumed. The demolition energy recovered during the EOL stage is found to be 0.32% of the total life cycle energy expended during the building project life cycle and is in agreement with findings of 0.30% by Chang et al. (2019). The small fraction of net demolition energy recovered during the EOL stage, which prima facie may appear to be insignificant but affords numerous benefits from a circular economy perspective. However, the EOL stage is linked to important environmental issues such as a) land use (for landfill dumps); b) contamination of soil and groundwater, solid waste management resulting from improper disposal of demolition waste; and c) saving of energy, and limited, non-renewable natural resources on account of reuse of secondary materials or recycling of material, and thus cannot be ignored. Accordingly, some studies have strongly argued in favour of extending the life span of old buildings instead of demolition and redevelopment, thereby resulting in the conservation of virgin material and avoidance of environmental degradation (Ding & Ying, 2019; Munarim & Ghisi, 2016).

The strategies for reducing energy requirements for demolition and improving the recovery of embodied energy from reuse/recycling of building demolition waste have already been discussed in Chapter 6 and, therefore, not being elaborated in this chapter.

7.4.1 Comparison with previous studies

The results of this study have been compared with those of some Indian and international studies conducted in the past, as shown in **Table 7.3**. It is observed that there is a significant variation between the amount of energy consumed by the case study buildings studied by different authors. Similar is the case of results on different buildings investigated by the same author.

The wide ranges of various types of energy in the above studies could be attributed to differences in system boundary selection, energy intensity of material production of various countries, types of construction material used and climatic conditions. For instance, the embodied energy results of this study, including recurring embodied energy, are higher than all the international and Indian studies referred to in **Table 7.3**. This is mainly due to the inclusion of MEP services and site features in the system boundary, as well as the inclusion of pre-design and design sub-stages in the pre-occupation stage of the building project life cycle. Higher values of operational energy demand reported by Pullen (2000a) pertain to case study buildings in southern Australia where central heating appears to have been used for the entire building. In contrast, only partial heating and cooling of individual living rooms in the residential towers is resorted to by using standalone air conditioners on as required basis in this study. Similarly, higher values of operational energy demand found by Keoleian et al. (2000) seem justified due to higher heating load as prevailing in the 'continental climate' of Michigan, USA, and the inclusion of recurring embodied energy in the operational energy estimates.

Table 7.3 Comparison of life cycle energy results with past studies

Geographical incidence	**Reference**	**Embodied energy (kWh/m^2/year)**	**Operational Energy (kWh/m^2/year)**	**Life cycle energy (kWh/m^2/year)**	**Remarks**
International	Pullen (2000a)	34-95	111-417	151-512	
	Villa et al. (2011)	16-80	62-228	143-281	
	Keoleian et al. (2000)	37.00	353.00*	390.00	* Includes recurring EE
	Humphrey et al. (2004)	97.07	288.71	385.78	
India	Devi and Palaniappan (2014)	67.27	116.00	186.00	
	Ramesh et al. (2012a)	31-44	250-348	302-390	
	This study#	56.28	264.61	320.89	# Recurring EE excluded
	This study&	122.09	264.61	386.70	& Recurring EE included

All figures are in primary energy terms

7.4.2 Sensitivity analysis

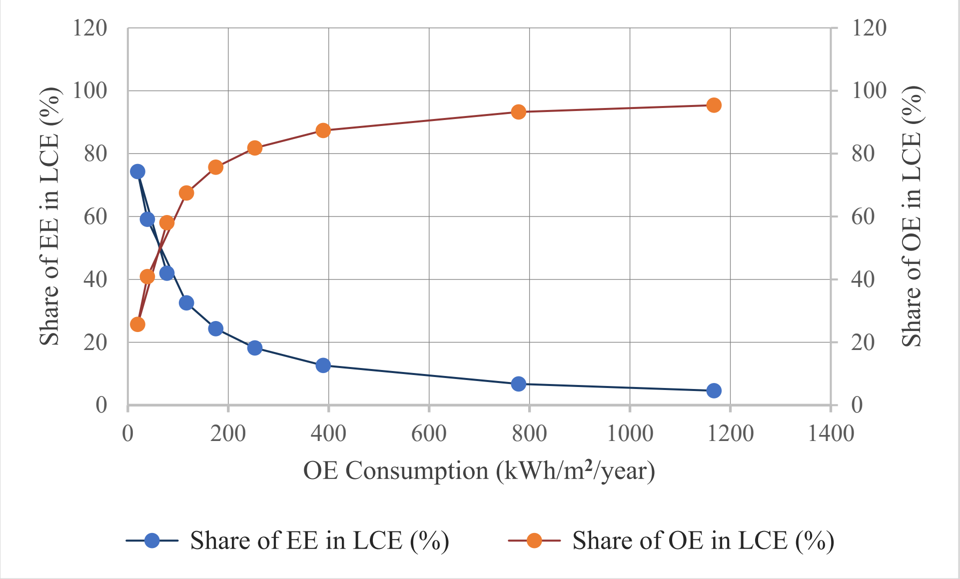
Sensitivity analysis was carried out to check the effect of variation in operational energy and building life span on life cycle energy. Details of test cases and corresponding changes in life cycle energy are given in **Table 7.4.** The variation in life cycle energy due to changes in operational energy corresponding to various test cases as per **Table 7.4** for building life spans of 50, 75 and 100 years is shown in **Figures 7.5, 7.6** and **7.7,** respectively.

Table 7.4 Effect of variation in operational energy and building life span on life cycle energy

Case No.	Variation in OE as proportion of base case (%)	OE ($kWh/m^2/year$)	LCE ($kWh/m^2/year$) (Life span 50 years)	LCE ($kWh/m^2/year$ (Life span 75 years)	LCE ($kWh/m^2/year$ (Life span 100 years)
Base case		77.83	134.11	115.35	105.97
Case 1	25	19.46	75.74	56.98	47.84
Case 2	50	38.92	95.20	76.44	67.29
Case 3	150	116.75	173.03	154.27	145.12
Case 4	225	175.12	231.40	212.64	203.50
Case 5	325	252.95	309.23	290.47	281.33
Case 6	500	389.15	445.43	426.67	417.53
Case 7	1000	778.30	834.58	815.82	806.68
Case 8	1500	1,167.45	1,223.73	1,204.97	1,195.83

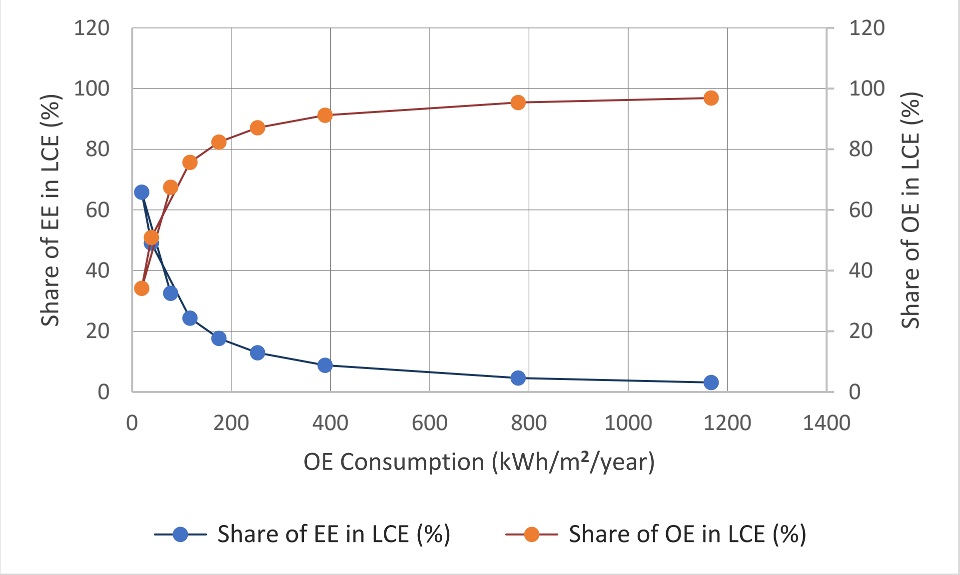
OE- operational energy   LCE- life cycle energy

It is observed that, firstly, for a given rate of operating energy consumption, an increase in building life span results in a reduction of life cycle energy requirements due to a decrease in embodied energy per annum. This emphasises the advantage of designing buildings with longer life span horizons and the need to prolong the life span of buildings with timely repair and maintenance. Secondly, the significance of embodied energy in the life cycle energy increases with a decline in operational energy consumption along with a decrease in building life span. This underlines the need for taking measures to reduce the initial embodied energy of the sub-systems through the proper selection of building materials and equipment for MEP services. Other measures for the reduction of initial embodied energy include reduction in wastage of material during on-site construction in the pre-occupation stage and effective project management to obviate the increase in initial EE on account of time and cost overruns.



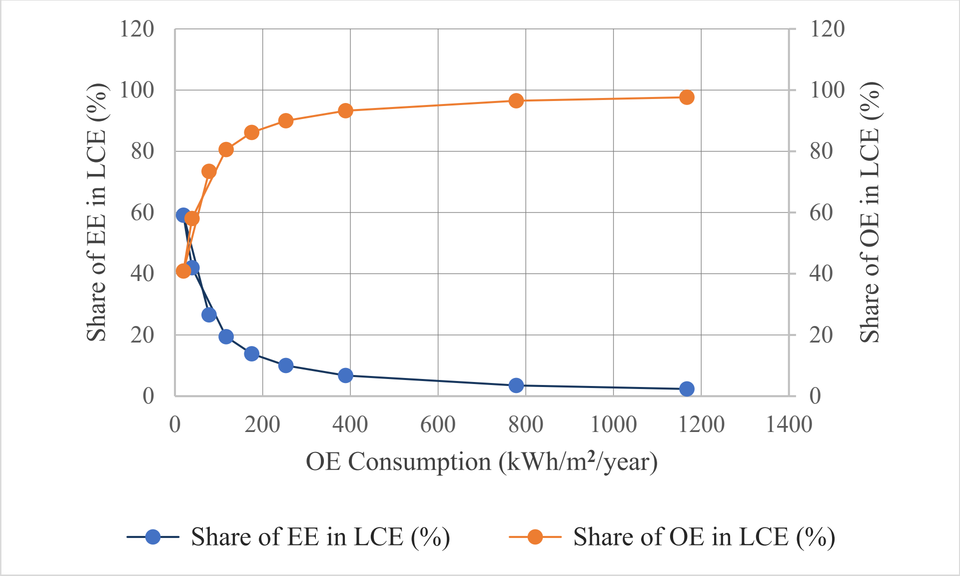
EE- embodied energy OE- operational energy LCE- life cycle energy

Figure 7.5 Share of EE (Initial EE + Demolition Energy) and OE in LCE with variation in OE consumption (building project life span 50 years (base case))



EE- embodied energy OE- operational energy LCE- life cycle energy

Figure 7.6 Share of EE (Initial EE + Demolition Energy) and OE in LCE with variation in OE consumption (building project life span 75 years)



EE- embodied energy OE- operational energy LCE- life cycle energy

Figure 7.7 Share of EE (Initial EE + Demolition Energy) and OE in LCE with variation in OE consumption (building project life span 100 years)

7.5 SUMMARY

The aim of this chapter was to analyse the energy requirements of a high-rise residential building project during its entire life cycle. The results of this chapter are mainly obtained from the analysis of the findings of the pre-occupation, occupation, and post-occupation stages as described in the preceding chapters. Results of this study indicate that building related sub-systems and non-building sub-systems consumed 49.20% and 50.80% of the total life cycle energy requirement of the building project, respectively. Amongst the MEP services, HVAC contributed to the highest proportion of life cycle energy, and sewage treatment plant required the lowest proportion of life cycle energy. The total embodied energy of the building project is found to constitute a large proportion of nearly 32% of the life cycle energy. Therefore, in a deviation from previous studies, which mainly targeted the reduction of operating energy demand, future strategies for improvement in the life cycle energy efficiency would also need to pay equal attention to decreasing the embodied energy of the building projects.

In terms of stage-wise energy requirements of the building project, the occupation stage accounted for the highest share of life cycle energy burdens. This stresses the need for using highly energy efficiency equipment, employment of professional facility management agencies, and stakeholder awareness to minimise the energy demand during the occupation stage. The study also underlines the relevance of the end-of-life stage in reducing environmental impact due to demolition waste disposal and saving scarce natural resources through reuse of secondary materials or recycling of scrap. The chapter concludes with a sensitivity analysis to check the effect of variations in operational energy demand and building life span on the life cycle energy consumption of the building project.

CHAPTER 8: SUMMARY AND CONCLUSIONS

8.1 BACKGROUND

Life cycle energy analysis is a holistic approach for evaluating the energy performance of buildings, which has the potential to contribute towards climate change mitigation. The analysis helps identify building project components and life cycle stages with high energy consumption. This could play an essential role in developing strategies for applying energy efficiency measures. In this study, the life cycle energy analysis of a high-rise residential building project has been conducted using the case study method of research. The study was conducted using a wider system boundary in terms of the stages of the building project life cycle and the scope of the building project. More specifically, the study included the following sub-stages, which are generally excluded by past studies: the pre-design and design sub-stages of the pre-occupation stage, the maintenance (B2) and repair (B3) sub-stages of the occupation stage, and the waste processing (C3) sub-stage of the post-occupation stage which pertains to reuse and recycling of the demolition waste. Moreover, the demolition energy required for the demolition of the RCC structure using controlled explosion has been computed based on primary data collected from the actual demolition of similar buildings by controlled explosion. The study was conducted with a systems approach by identifying the various sub-systems of the building project based on their functional usage. The study also considered all the components of a high-rise residential project, including the MEP services and the site features, which are rarely included by past studies in the life cycle energy analysis of buildings.

This chapter aims to briefly summarise the key results, conclusions drawn from the study, and the recommendations. It also outlines the research contributions, implications, and limitations, followed by some suggestions for further research. The findings and conclusions of the study have been discussed in four subsections: pre-occupation stage, occupation stage, post-occupation stage, and life cycle, in the summary and conclusions section below.

8.2 SUMMARY AND CONCLUSIONS

8.2.1 Energy analysis during the pre-occupation stage

The first objective of this research is to estimate the embodied energy of a high-rise residential building project during the pre-occupation stage. Pre-design and design sub-stages, which are generally ignored, consumed nearly 3% of initial embodied energy. The design sub-stage assumes importance as the initial EE wasted on frequent rework can be minimised by proper design of buildings and freezing of developer requirements/specifications before the commencement of construction work.

In the building portion, structural elements, i.e., steel, concrete, bricks and cement, collectively accounted for 98.54% and 90.27% of total weight and total initial embodied energy, respectively. At the whole building project level, the residential tower and parking sub-systems consumed a large share of nearly 68% of the total initial embodied energy. MEP services and site development features accounted for the remaining 32%. Thus, structural and envelope elements, and MEP services offer considerable scope for embodied energy optimisation.

As steel accounted for the highest share of the total EE in the building portion, it is recommended that recycled steel may be used in place of virgin steel till such time a low energy-intensive material is developed by researchers, which could replace or reduce the use of steel in the building construction. Similarly, concrete is found to have the second most significant contribution to initial EE. Therefore, the construction of buildings with composite material comprising structural steel and concrete or shear walls in place of RCC framed structure needs to be examined from energy considerations.

The findings also call for effective project management to avoid the increase in initial EE due to time and cost overruns as experienced during the construction phase of this study. In addition, it is recommended that developers provide options for limited customisation of apartments to owners during the construction to avoid an undue increase in embodied energy on the upgrades of newly constructed apartments.

8.2.2 Energy analysis during the occupation stage

The second objective of this research is to study the energy demand of various sub-systems in a high-rise residential building project during the occupation stage. In this stage, recurring energy is consumed on repair, maintenance, and replacement. Additionally, operating energy is consumed on lighting, space heating and cooling, and operation of services. The primary operational energy demand of all sub-systems is estimated to be about 264.61 kWh/m^2/year, and the total primary energy footprint of occupation stage (includes recurrent EE and operational energy) is found to be 330.42 kWh/m^2/year.

Compared to building related sub-systems and site features, MEP services, in general, expended a higher proportion of recurring energy with respect to the initial embodied energy. This occurs due to a higher frequency of replacements of MEP components during the building project life cycle.

Amongst the MEP services, the HVAC sub-system accounted for the highest proportion of recurring EE with respect to initial EE. This could be attributed to a comparatively higher number of replacements and a higher maintenance cost. Therefore, there is a need to examine the trade-off between cost, durability and energy efficiency of materials, especially in the case of the MEP equipment at the time of replacements. Moreover, replacements of MEP equipment should be taken as a last resort after exploring options of remanufacturing or refurbishment.

Similarly, MEP services consumed about 57% of the total direct OE amongst all the sub-systems, wherein the HVAC sub-system alone accounted for approximately 44% due to significant energy requirements for space cooling and heating. Therefore, techniques such as passive solar architecture and HVAC equipment with higher energy efficiency may be employed to reduce direct OE requirements. The passive solar architecture could comprise the use of building envelope material with low thermal transmittance (e.g., cavity walls, insulation material, double/triple glazed windows), use of shading devices, and designing window-to-wall ratio for optimum rate of infiltration. Additionally, the use of smart controls for the operation of MEP equipment may be resorted to for improvements in the energy efficiency of these services.

It is also observed that the residential tower sub-system consumed the highest share of indirect energy for facility management functions such as administrative, technical, security, and housekeeping services, apart from the cost of building insurance. This emphasises the need for higher utilisation of electronic surveillance for security and access control, and the use of electro-mechanical labour-saving devices for housekeeping services to reduce indirect energy consumption during the occupation stage.

The majority of the existing building stock comprises conventional buildings, which consume more energy than low-energy buildings. Therefore, a country-specific action plan is imperative for undertaking cost-effective energy efficiency measures such as revision of building energy codes, energy audit and retrofitting of existing buildings to reduce the operating energy demand of the existing build stock.

8.2.3 Energy analysis during the post-occupation stage

The third objective of this research is to investigate the demolition energy consumption of a high-rise residential building project during the post-occupation stage. Building-related sub-systems (residential towers and parking) contributed to about 81% of the total demolition waste generated and 80% of the total demolition energy consumed on deconstruction/demolition and transportation of waste for reuse/recycling or disposal by all sub-systems. On the other hand, though non-building sub-systems (MEP and site features) generated approximately 19% of the total demolition waste and consumed about 20% of the total demolition energy, they were able to recover a proportionately higher amount of demolition energy (25.72%) from reuse/recycling mainly due to higher metal content of MEP services in the demolition waste. Hence, the influence of non-building sub-systems on the outcome of a demolition project can no longer be ignored.

Concrete and non-concrete inert waste accounted for nearly 95.6% of the total demolition waste generated, while metals, PVC, and timber scrap collectively make the balance of approximately 4.4%. Concrete contributed to the highest proportion (73.20%) of demolition waste and consumed the highest share of demolition energy (84.46%), while steel scrap for recycling enabled the highest amount of embodied energy recovery (90.46%). However, most of the energy recovered from the recycling of steel scrap was neutralised due to the high rate of energy consumption in the demolition of concrete.

Therefore, the long-term strategy to make the end-of-life stage of a building more sustainable could be to minimise the energy requirement for demolition and maximise the energy recovery from the reuse/recycling of demolition waste. The requirement of demolition energy can be reduced by innovative methods such as the use of prefabricated structures and design for disassembly approach during initial construction. Furthermore, onsite recycling of waste can help reduce the energy consumption on transportation of waste for off-site recycling or disposal.

Similarly, the recovery of energy from the reuse/recycling of demolition waste can be increased by policy initiatives such as an increase in stakeholder awareness, establishment of material banks, revision of codes for the use of recycled material in new construction, incentivising recycling of waste by grant of rebate to developers for subsequent new constructions, and robotic segregation of demolition waste. These measures would also result in the reduction of construction and demolition (C&D) waste to decrease the landfill space requirements, apart from reducing the demand for extraction of raw material for new construction.

The present rate of waste generation of 400 kg/m^2 laid down by the ULB is grossly underestimated as compared to the findings of this study (1715 kg/m^2) and needs to be revised for realistic resource allocation for better waste management.

Planning for demolition needs to form part of the construction planning stage to cater for critical requirements such as safety distances from neighbouring buildings, deployment of mechanical demolition equipment, layout of service lines, and space requirements for loading and transportation of demolition waste.

8.2.4 Energy analysis during the life cycle

The fourth objective of this research is to analyse the overall energy requirements of a high-rise residential building project during its entire life cycle. In the current study, building related[1] sub-systems and non-building[2] sub-systems (MEP services site features) accounted for 49.20% and 50.80% of the total life cycle energy requirement of the building project, respectively. MEP and site features sub-systems exhibited a significant share of energy recovery or consumption, ranging from about 20% to 55% during various life cycle stages, and thus demand due research attention. These findings emphasise the need to include the complete system boundary, i.e., all sub-stages of the life cycle and all components of a building project, to enable realistic energy analysis and formulation of strategies for reduction in energy and environmental burdens of the building projects.

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[1] building related sub-systems pertain to residential tower and parking sub-systems.

[2] non-building sub-systems include. MEP services, site development, sports, and site beautification sub-systems

In terms of the type of energy consumption, the total embodied energy (IEE+REE-DE) of the building project is found to constitute a large proportion of nearly 32% of the life cycle energy, with operating energy accounting for the balance of about 68%. Therefore, two important observations are: firstly, approaches to minimise the life cycle energy will have to consider both embodied energy as well as operating energy, unlike past studies which primarily focused on improving the operational energy efficiency of buildings; secondly, during the occupation stage, the demand for various services is mainly customer (occupant) driven.

Therefore the operational energy consumption would be considerably influenced by the occupant behaviour (He et al., 2021; Karatas et al., 2016). This stresses the necessity of employing intervention strategies to mould occupant behaviour towards energy conservation.

Demolition energy consumed by all sub-systems during the demolition process, including energy required for transportation for recycling and waste disposal, is found to be 3.55 kWh/m^2/year, equivalent to 0.91% of the life cycle energy. On the other hand, embodied energy recovered from the reuse/recycling of scrap amounted to 4.77 kWh/m^2/year. On the whole, the energy footprint of the post-occupation phase is estimated as (-) 1.22 kWh/m^2/year /year, equivalent to (-) 0.32% of the life cycle energy.

In terms of the stages of the building project life cycle, the pre-occupation, occupation and post-occupation stages consumed 14.87%, 85.45% and 0.32% of the life cycle energy, respectively. The overall life cycle energy demand of the building project is estimated at 386.70 kWh/m^2/year. The occupation stage (operation stage) accounts for the highest share of life cycle energy burdens.

The present study performs life cycle energy analysis at the building project scale. The lower proportion of initial embodied energy (IEE) in the life cycle energy (about 15%) as compared to a partially air-conditioned H-MIG type residential building in India (nearly 30%) reported in a study by Devi and Palaniappan (2014) at the building scale could be attributed to: a) the decrease in IEE due to the inclusion of basement in the total BUA, which has very few partition walls, and use of less energy-intensive flooring material in the basement (PCC) as compared to that in the residential apartments (marble/tiles), b) the residential apartments in this study being fully air-conditioned, and c) the inclusion of indirect operating energy consumed on facility management activities such as the operation of services, the provision of security and housekeeping in the system boundary.

Geographical representativeness needs to be ensured while estimating embodied energy consumption, and results of energy analysis should be expressed in terms of primary energy instead of final energy to avoid inaccuracy and for better comparability with other studies.

The type of material and equipment selected for initial construction has a bearing on the energy and environmental burdens of the sub-systems during one or more downstream stages of the building project life cycle. Environmental Product Declarations (EPD) (Gelowitz & McArthur, 2017) can assist in the material selection at the design stage by comparing the products with respect to their energy and environmental impacts but are seldom available. This necessitates a policy framework for the mandatory provision of EPD by the manufacturing industry. Country-specific data on embodied energy coefficients and the useful life of material may be used for the selection of construction material until the availability of EPD data improves.

It was also observed during the study that the embodied energy analysis of building projects is highly data intensive. Lack of data availability due to absence of data capture and data sharing regulations may compel the researchers to make assumptions, leading to inaccuracies in the data and results. This highlights the need for a policy framework on mandatory archiving and sharing of data at the urban local authority (ULB) level to enhance the accuracy of findings and assist the research environment.

Different countries have different energy intensities because of variations in energy mix, energy prices, and industrial and power sector efficiencies. Therefore, a study of this kind in the Indian environment will contribute to the knowledge repository and enable cross-comparison with studies across similar economies.

8.3 STRATEGY RECOMMENDATIONS

The overall strategy for improvement in energy performance, derived from the findings of this study, is suggested below in a stage-wise manner:

***During the pre-occupation stage**, design the buildings for low embodied energy burdens and low operating energy requirements*. This could be achieved by using passive solar architecture, durable, low embodied energy and recycled materials, materials with low thermal transmittance, and materials with higher recycling potential, duly evaluated from a life cycle perspective at the design stage. Other measures, such as employing project management consultants and reducing construction waste, can further help reduce energy consumption during the pre-occupation stage.

During the occupation stage, *minimise operating and recurrent embodied energy consumption.* The operating energy consumption could be optimised through using energy-efficient equipment and appliances, employment of facility management agencies, and moulding of occupant behaviour. Additionally, energy from renewable sources may be used instead of non-renewable sources to lower the environmental impact of the occupation stage. The consumption of recurrent energy may be reduced by promoting the usage of durable material that requires low maintenance, improvement in quality of workmanship during initial construction to obviate the need for frequent repairs, and regular repair and maintenance of building components and equipment to decrease the number of replacements. The life span of buildings should also be prolonged through periodic repair and maintenance, and demolition of buildings may be carried out only as a last resort after evaluating the options for renovation and new construction.

During the end-of-life stage, *minimise energy consumption on demolition and maximise the recovery of embodied energy from the reuse/recycling of demolition waste.* The requirement of demolition energy may be reduced by using innovative methods such as design for deconstruction and robotic demolition. Thereafter, the recovery of embodied energy should be maximised by increasing the recovery of scrap using techniques such as robotic segregation and by increasing the proportion of reuse/recycling of demolition waste.

Despite the above recommendations, one of the foremost options to minimise the energy and environmental impact of building projects would be to build less by reducing the built-up area per capita, but with better design for higher space utility.

8.4 RESEARCH IMPLICATIONS

The findings of this study are suggestive of some important research implications for key stakeholders, as outlined in succeeding paragraphs.

Policymakers: The following policy initiatives need urgent attention:

Creating a sustainable market for energy efficient (low-energy) buildings by promoting stakeholder awareness on energy and environmental impact of material and energy use in buildings, and economic benefits of energy conservation; and incentivising purchase of energy efficient properties by lowering initial registration fees and rates for annual property tax.

Formulation of an institutionalised mechanism for data archiving and data sharing for use by stakeholders for promoting building energy conservation and mandating the provision of environmental product declaration (EPD) on construction material and equipment by the manufacturing industry to assist in selecting energy efficient material by designers, developers and property owners during initial construction and subsequent replacements.

Revision of guidelines for effective waste management based on realistic rates of C&D waste generation depending on the type of building structure; incentivising recycling of demolition waste and use of recycled material in new constructions by means of rebates on construction permits; revision of building energy conservation codes for higher coverage of plinth area; energy labelling of non-building sub-systems such as MEP services similar to the labelling of buildings to ensure a holistic energy labelling of the complete building project; laying down higher rates of property tax for sprawling residential buildings that have a higher per capita plinth area (polluter-pays-principle) and use of collected revenue for energy efficiency initiatives by the state agencies.

Practitioners: Design consultants should examine options such as design for deconstruction and use of prefabricated components. Designers may also use EPDs for the selection of materials during initial construction. Design alternatives may be evaluated by energy management consultants from a life cycle perspective. Developers need to improve the quality of initial construction to reduce the cost/embodied energy incurred on repair and maintenance by upskilling construction workers, promoting the usage of modern construction equipment, and ensuring a reduction in the generation of construction waste due to rework. Developers should employ project management consultants (PMC) to avoid EE consumption due to time and cost overruns. In addition, during initial construction, developers may involve experienced facility management professionals in the selection of such materials and equipment that would require low maintenance, have a longer service life, and also require less energy during the occupation stage.

Customers and resident associations: Customers should seek limited customisation from developers during purchase agreements and employ professional agencies for facility management. Additionally, they need to select materials and equipment with higher energy efficiency during replacements and ensure periodic repair and maintenance to prolong the useful life of equipment and the life span of buildings, thus saving increased energy burdens on new construction due to the demolition of existing assets.

Researchers: Researchers can contribute through innovations in the various fields to develop new composite materials to reduce the usage of concrete, low embodied energy materials, and materials with higher recycling potential. The research should also focus on exploring new design for deconstruction techniques, and improvement in technology for robotic demolition and robotic segregation of waste.

8.5 RESEARCH CONTRIBUTION

The main contributions of this study are enumerated as follows:

- First, the study proposes a systematic methodology that could be replicated by other studies to estimate the life cycle energy of sub-systems that comprise a building project. Moreover, based on the findings of similar studies on a few typical structures prevailing in a region, this methodology can also be extended to estimate the life cycle energy of building projects at the regional level.
- Secondly, it highlights the necessity to consider the complete system boundaries in terms of the life cycle stages and the components of a building project while conducting the energy analysis for formulating energy optimisation interventions.
- Thirdly, it stresses the relevance of MEP services and site features for improvement in the energy performance of building projects.
- Next, the study ascertains the energy required for the demolition of a high-rise residential building by controlled explosion using data from actual demolition of similar buildings in the same region. The methodology used in this study would be helpful in realistic assessment of demolition waste and demolition energy of building projects which could be developed into a guideline through further studies on the subject, thereby filling a vital gap in the area of building demolition by controlled explosion.

- Additionally, the study emphasises the need for urgent policy initiatives on issues such as the mandatory provision of EPD by the manufacturing industry, the establishment of a formal data exchange system on building construction projects, stakeholder awareness for creating a sustainable demand for energy efficient buildings, and incentivising reuse/recycling of demolition waste.
- Finally, the findings of this study are expected to be helpful to stakeholders in identifying opportunities for reduction in the energy and environmental impacts and making the building projects more sustainable.

8.6 LIMITATIONS OF THE STUDY

The results of this study are based on the assumption that the average annual operating energy consumption of the building project will remain constant throughout the life span of 50 years. However, the operating energy consumption may change due to change in climate, an increase in number of appliances, change in energy efficiency of MEP equipment and building envelope elements after replacements, and variation in occupant behaviour. Moreover, the primary energy factor itself may change due to a change in the energy mix, e.g., a shift from coal to natural gas (having higher fuel efficiency) for power generation and improvement in the efficiency of power generation, transmission and distribution network.

During the occupation stage, the recurring embodied energy (REE) of the building projects may be affected due to type of method used for REE estimation, changes in embodied energy coefficients of construction material with improvements in the energy efficiency of the manufacturing industry with time and changes in construction technology. Similarly, variations in operating energy demand could also occur due to future climate changes (Berardi & Jafarpur, 2020).

During the post-occupation stage, the costs and demolition energy incurred on building project demolition may change due to advancements in demolition techniques over the long span of 50 years or more. Similarly, the rates of scrap material may change with time and due to fluctuations in market prices. In addition, as the city grows in future, the transport distances to waste processing plants, scrap agencies and landfills are likely to increase.

The above limitations may cause uncertainty in the results of this study. Lastly, as the results are based on only one case study building project, further studies would be required on similar buildings for validation and to improve the reliability of the findings.

8.7 FUTURE RESEARCH

The infrastructural components of buildings considered outside the system boundary of the present study, such as rail, road, water and air transportation network, power generation and distribution, municipal sewage and stormwater drainage, and telecommunication, also consume large amounts of embodied energy. The share of embodied energy of these infrastructural components to various building projects in a locality is a relevant subject for further research on energy analysis of urban forms.

Further research may be carried out on the life cycle energy analysis of similar buildings to validate the findings of this study before the finalisation of the policy framework. Similar studies could also be undertaken for non-residential buildings (e.g., office buildings, commercial buildings and industrial buildings) for further classification of demolition waste and demolition energy based on the functional usage of a building project.

Energy analysis of compact development as obtainable in high-rise residential complexes may be compared with spread-out low-rise residential complexes, and town planners may consider the findings for reducing the energy and environmental burdens of future developments.

The current study focussed only on one indicator of environmental performance, i.e., energy performance. Further studies may be undertaken on other environmental impacts such as climate change, ozone depletion, land use, and acidification caused during the life cycle of building projects. Additionally, apart from the environmental issues, the social and economic aspects of building projects may also be examined by future studies to make the building projects more sustainable.

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APPENDIX A: RESEARCH METHODS AND TOOLS USED BY PAST STUDIES

Table A-1 Research methods and tools used for embodied energy estimation

	Method category	Research methodology/ Mathematical tool used	Author reference
1	Experimental Investigations/energy management techniques	Action research method, expert workshops, Post Tensioned construction methods.	Gottsche et al. (2016), Wilson et al. (2019), Miller et al. (2015).
2	Inventory analysis	Input–output–based hybrid analysis, Inventory of Carbon and Energy (ICE) database from Hammond and Jones, multi-regional input-output (MRIO) analysis, structural path analysis (SPA), and process-based LCA model 2002, U.S. Benchmark Accounts for constructing the IO model, Input-output analysis, Ecoinvent v2.0 inventories, BEDEC database, ECOTECT, initial cost accounts for the data from RS Means, IMPACT 2002+ method, process-based hybrid life cycle inventory models, material flow analysis (MFA) modelling, Environmental Product Declarations (EPD) and Ecoinvent 3.3.	Aye et al. (2012), Gaspar and Santos (2015), Iddon and Firth (2013), Hong et al. (2018), Hong et al. (2019), Dixit et al. (2015), Treloar et al. (1999), Bribián et al. (2009), Utama and Gheewala (2009), Han and Srebric (2015), Hong et al. (2016), Chang et al. (2014), Saadah and AbuHijleh (2010), Lewandowska et al. (2015), Treloar et al. (2001c), Sandanayake et al. (2017), Chang et al. (2012), Moncaster and Symons (2013), Sandberg and Brattebø (2012), Volf et al. (2018). .

Table A-1 Research methods and tools used for embodied energy estimation (contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
3	Life Cycle Assessment (LCA)	LCA, SimaPro software, Footprint Reporter, the Global Emission Model for Integrated Systems (GEMIS), ISO 14020, ISO 14040, ISO 14025, LCA coupled with LCC, BIM-LCA method, Autodesk Revit, LCA- Exergetic life-cycle assessment (ELCA), Ecoinvent database, BIM-LCA integration using Tally application in Autodesk Revit(BIM), target value design (TVD), Green building studio, BIMWASTE tool, ATHENA Impact Estimator (IE), SIMIEN-simulation software, Attributional and Consequential LCA, Calculation tool DK LCACalc, design tool WUFI Pro, Eco2soft, Eco-Indicator, Environmental Product Declarations (EPD), analysis method Impact 2002+, SimStadt, Umberto software-German ifu institute, Hamburg, embodied energy composition analysis, streamlined probabilistic LCA.	Giama and Papadopoulos (2015), Airaksinen and Matilainen (2012), Flower and Sanjayan (2007), Wu et al. (2012), Ye et al. (2018), Shadram et al. (2016), Pargana et al. (2014), Dong and Ng (2015), De Meester et al. (2009), Bastos et al. (2016), Xing et al. (2008), Su and Zhang (2010), Hoxha and Jusselme (2017), Hoxha and Jusselme (2017), Li and Chen (2017), Sedláková et al. (2015), Nußholz et al. (2019), Itard and Klunder (2007), Quale et al. (2012), Gan et al. (2017), Thormark (2000), Pearlmutter et al. (2007), Russell-Smith et al. (2015), Chau et al. (2007), Seo et al. (2015), Ajayi et al. (2019), Lützkendorf et al. (2015), Kua and Kamath (2014), Verbeeck and Hens (2010), Silvestre et al. (2014), Marsh (2016), Nordby and Shea (2013), Honic et al. (2019), Koroneos and Dompros (2007), Ferrández-García et al. (2016), Hoxha et al. (2017), Papadopoulos and Giama (2007), Boscato et al. (2018), Ghaemi and Amidpour (2019), Huberman and Pearlmutter (2008), Asif et al. (2007), Davies et al. (2014), Sierra-Pérez et al. (2016), Bribián et al. (2011), Weiler et al. (2017), Chong and Hermreck (2010), Islam et al. (2015), Hester et al. (2018)..
	Life Cycle Cost Analysis (LCCA	LCCA, Stepwise2006 method, ecoinvent database, Multi Criteria Decision Making (MCDM) method, i.e., the Analytic Hierarchy Process (AHP) method.	Morrissey and Horne (2011) Talang and Sirivithayapakorn (2018).
	Life Cycle Energy Analysis (LCEA)	LCEA Method.	Giordano et al. (2015), Kofoworola and Gheewala (2009), Hernandez and Kenny (2010a), Ramesh et al. (2012b), Chau et al. (2017), Ding and Forsythe (2013), Ding (2007), Fay et al. (2000).

Table A-1 Research methods and tools used for embodied energy estimation (contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
4	Mathematical tools/ calculations	Arithmetic calculations, from project drawings, quantitative survey, field survey - energy used for earthmoving operations, fuzzy multi-criteria decision making (MCDM), Fuzzy set theory, Monte Carlo method, Multi-objective optimization module implemented in Grasshopper by using Octopus, multiple linear regression models, Quantitative analysis, simple correlation analysis (r2, coefficient of determination) and a simple linear regression analysis, Power series approximation (PSA) method, symmetric weighting approach.	Davies et al. (2015), Menzies and Wherrett (2005), Cole and Kernan (1996), Thormark (2002), Dimoudi and Tompa (2008), (Thomas et al. (2019), Cavalliere et al. (2019), Devi and Palaniappan (2017), Kabak et al. (2014), Chau et al. (2012), Shadram and Mukkavaara (2018), Davies et al. (2013), Sharrard et al. (2007), Dixit (2017b), Kristjansdottir et al. (2018).
5	Propriety tools/models	Multi-Objective Building Optimization tool, Aggregated data quality indicator (ADQI) method, Analytical hierarchy process (AHP), Database of macro components, Design Builder software, BIM - Building information modelling, GBR Systems general method, LIDER+CALENER programs calculate energy efficiency, integrated modular envelope system, wxPython, Databases for embodied energy figures implemented using Buzhug, Microsoft Visual Studio environment, Standard Development Kit (SDK) for Revit 2016, quota-based carbon tracing (QCT) model, Waste Reduction Model, worksheet tool: IREEA (Initial and Recurring Embodied Energy Assessment).	Harkouss et al. (2018), Gervásio et al. (2014), Gan et al. (2018), Lee et al. (2011a), Lastra-Bravo et al. (2013), Stephan et al. (2012), Nizam et al. (2018), Fang et al. (2018), Diyamandoglu and Fortuna (2015), Giordano et al. (2017), Najjar et al. (2017).

Table A-2 Research methods and tools used for operational energy estimation

	Method category	Research methodology/ Mathematical tool used	Author reference
1	Energy simulation tools/ software	SIMIEN, DOE, TRNSYS15 and the multizone air flow program COMI, AccuRate software for heating and cooling loads, EnergyPlus dynamic thermal simulation engine, IDA Indoor Climate and Energy (IDA-ICE) tool, Lesosai software (E4tech, 2008), EcoRoof model by Sailor (2008), VIP+ energy simulation software, DIN V 18599- energy certification standard, ANN-exhaustive-listing method for optimization, Design Builder V5 software (with Energy Plus simulation engine), optimization-based analysis using DOE.2-2, energy simulation-commercial software, simulation using AccuRate, dynamic simulations using ESP-r and BuildOpt-VIE programs, Data-driven Urban Energy Simulation (DUE-S), Urban Building Energy Models (UBEM), Machine Learning (ML) techniques, EnergyPlus and Ecotect, Revit architectural model and Edilclima EC770 Plug-In, performance-based simulation tools, EC501 -energy simulation software, DOE-2 whole building energy simulation engine, LCA-using SimaPro 7.1 software, dynamic thermal simulation engine-COMFIE, ECOTECT-dynamic building analysis software, Archsim in Grasshopper with EnergyPlus, CHENATH simulation engine within NatHERS, building energy performance simulation (BEPS) tools, Building Energy Simulation programs, BEEPS (Building Environment and Energy Performance System) software, BRE Domestic Energy Model (BREDEM), energy-rating software – AccuRate, Quick II thermal simulation software (TEMMI Ltd), machine learning, Energy simulation.	Lützkendorf et al. (2015), Cole and Kernan (1996), Verbeeck and Hens (2010), Morrissey and Horne (2011), Ramesh et al. (2012b), Aye et al. (2012), Han and Srebric (2015), Gan et al. (2018), Kristjansdottir et al. (2018), Tettey et al. (2019), Hollberg et al. (2018), Lin and Yang (2019), Pathirana et al. (2019), Kwag et al. (2019), Yoo et al. (2015), Ren et al. (2014), Katunsky et al. (2013), Sarto et al. (2012), Nutkiewicz et al. (2017), Erba et al. (2017), Nunes et al. (2013), Shabunko et al. (2018), Davila et al. (2016), Seyedzadeh et al. (2019), Saroglou et al. (2017), Ugliotti et al. (2016), Hien et al. (2000), Fasano and Zinzi (2006), Hernandez and Kenny (2010a), Jaber and Ajib (2011), Ihm and Krarti (2012), Desideri et al. (2014), Santos et al. (2014), Martinaitis et al. (2015), Chung and Rhee (2013), Zomorodian and Tahsildoost (2018), Utama and Gheewala (2009), Shadram and Mukkavaara (2018), Fay et al. (2000), Lopes et al. (2017), Karlsson et al. (2007), De Santoli and Felici (2005), Iddon and Firth (2013), Islam et al. (2015), Pearlmutter et al. (2007), Ngo (2019).

Table A-2 Research methods and tools used for operational energy estimation contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
2	LCA, LCCA, LCEA	LCA coupled with LCCA, LCA-based environmental impact assessment tools, life cycle energy analysis (LCEA).	Ottelé et al. (2011), Wu et al. (2012), Sproul et al. (2014), Giordano et al. (2015; Wagner et al. (2014), Kofoworola and Gheewala (2009), Hernandez and Kenny (2010a), Meex et al. (2018).
3	Proposed framework/ model	GIS integrated data mining methodology framework, Neighbourhood Urban Energy Modelling, energy audit, Energy Performance indices, surrogate model, energy simulation energy monitoring, life cycle cost analysis, occupant survey energy modelling, Spatial Data analysis model, sequential mixed methods study, The Smart City Energy Assessment Framework tool (e-SCEAF), Building for Environmental and Economic Sustainability, (BEES) model, Behaviour modelling, walkthrough energy audit, DNAS framework, homology based mapping process and generative agents for design of an HVAC system, energy- consumption evaluation, GIS based method, Energy performance certificate databases, Energy performance certificates, dynamic energy benchmarks, methodology based on a tabu search, comprehensive framework, survey, focussed group discussion, development of the contribution indices, TOBUS method -and software - a European decision making tool, TABULA method-a harmonised structure for the creation of national typologies, DATAMINE database and analysis tool, resistance-capacitance network (RC-network) model, IDA, a typical tool for dynamic building simulation, PCM treatment methods, thermal simulation model, non-destructive testing method (thermal imaging).	Ma and Cheng (2016), Urquizo et al. (2018), Escrivá-Escrivá et al. (2011), Melo et al. (2016), González et al. (2011), Martín-Consuegra et al. (2018), Day and Gunderson (2015), Papastamatiou et al. (2017), Babaizadeh et al. (2015), Hong et al. (2017), Mekhilef et al. (2014), Belafi et al. (2019), Brahme and Mahdavi (2003), Salat (2009), Mutani et al. (2016), Gangolells et al. (2016), López-González et al. (2016), Liu et al. (2017), Ruiz et al. (2014), Alves et al. (2018), Balaras et al. (2002), Dascalaki et al. (2011), Dascalaki et al. (2010), Airaksinen and Matilainen (2012), Lai and Chiang (2006), Virk et al. (2015), Berardi (2012), Taileb and Dekkiche (2015).

Table A-2 Research methods and tools used for operational energy estimation contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
4	Proprietary software/ model	MOOSAS -simplified energy, consumption prediction model, home energy management systems (HEMS), computer program DEROB-LTH, version 99.01, thermal simulation employing Quick II software (TEMMI, Ltd.), primary energy and CO_2 emissions are calculated using CALENER conversion factors, BESLCI program developed by Huang, dynamic Beuken-model, thermal radiation models, glazing models, Energy Performance Advice (EPA) tool.	Li et al. (2018), Bribián et al. (2009), Su and Zhang (2010), Feist et al. (2019), Sunikka (2006), Wilson et al. (2019), Thormark (2002), Huberman and Pearlmutter (2008).
5	Miscellaneous methods (National standards, Literature)	DIN V 4108-6:2003. National Australian Built Environmental Rating Scheme (NABERS), energy rating methods, sustainability rating systems, Literature.	Sunikka and Galvin (2012), Thomas (2010), Ballarini and Corrado (2009), Friedman and Cammalleri (1997), Berardi (2012).
6	Mathematical tools/ calculations	Energy Efficiency Analysis, A multiple regression model, Estimation models, regression models, multi-criteria benchmarking approach, data-driven savings analysis, cluster analysis, decision tree (DT) analysis, and analysis of variance (ANOVA), energy modelling, Bayesian Regression combined engineering and statistical bottom-up model, Delphi-Analytic Hierarchy Process(AHP) framework, technical measurements, Semi-structured interviews, statistical analysis and GIS Platform, demographic-based probability neural networks, ANN, statistical analysis. multiple linear regression method, variable heating degree-days method, Monte Carlo uncertainty analysis. 3D numerical analysis using CFD for PCM. Numerical simulation using finite element method, energy bills.	Flucker and Tozer (2013), Steadman et al. (2014), Lasshof and Stoy (2016), Lasshof and Stoy (2016), Mathew et al. (2015), Heidarinejad et al. (2014), Park et al. (2016), Choudhary (2012), Theodoridou et al. (2012), Papadopoulos and Kontokosta (2019), Grossmann et al. (2016), Galante and Torri (2012), Diao et al. (2017), Magalhães et al. (2017), Kazanasmaz et al. (2014), Wei et al. (2018), Yoo et al. (2013), Robati et al. (2019), Muthuvel et al. (2015), Kočí et al. (2016), Ding (2007).

Table A-3 Research methods and tools used for demolition energy estimation

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
1	Field measurements	Hybrid demolition, mechanical demolition, deconstruction.	Pun et al. (2006).
2	LCA and BIM	LCA-to assess different construction and demolition waste (C&DW) management plans during design phase, ISO 14040:2006, BIM and LCA, Hybrid life cycle analysis.	Martínez et al. (2013), (Moncaster & Symons, 2013), Dodoo et al. (2009).
3	Mathematical tools/ modelling	Attributional or consequential modelling approaches, agent-based modelling (ABM) approach - Modelling-verification-experimentation.	Sandin et al. (2014), Ding et al. (2016).
4	Proposed framework	Revit 2017, disassembly and deconstruction analytics system (D-DAS), Life cycle energy analysis, extension of the multi-mode resource constrained project-scheduling problem (MMRCPSP).	Akanbi et al. (2019), Schultmann and Sunke (2007).

Table A-4 Research methods and tools used for life cycle energy estimation

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
1	Inventory analysis + mathematical calculations	Hybrid input-output analysis, national statistical energy data, energy balance tables, Input-output tables, energy meter readings, based on Building Owners and Managers Association (BOMA) targets, LCI Inventory analysis, field data.	Zhang and Wang (2016), Suzuki and Oka (1998), Treloar et al. (2001b), Kofoworola and Gheewala (2008).
2	Inventory analysis + energy simulation tool	Annual loss factor (ALF) version 3.0 – an energy simulation tool, literature, dynamic calculation method GEM-21P for assessing the CO_2 emissions, Life Cycle Impact Assessment (LCIA) procedure – ReCiPe-method, HASP- an energy simulation program, SimaPro 7 software, EnergyPlus3, Inventory of Carbon and Energy (ICE) Version 1.6a (Hammond and Jones, 2008, Ecoinvent database, SimaPro, Designer's Simulation Toolkits (DeST), LCA, energy simulation -Environmental Systems Performance-research (ESP-r) software, SimaPro life cycle inventory software, LCC with energy simulation, field data collection, DEAM database, - eQuest, BIM enabled LCA, Autodesk Revit 2015, eBalance software, Chinese Life Cycle Database, Designbuilder (Version 4.5.0.148) based on EnergyPlus 8.3, SimaPro with Calener Vyp energy simulation software.	Mithraratne and Vale (2004), Thormark (2006), Baek et al. (2013), Attia (2016), Hernandez and Kenny (2010b), Gong et al. (2012), Saiz et al. (2006), Lee et al. (2011b), Schmidt et al. (2004), Scheuer et al. (2003), Azari (2014), Yang et al. (2018), Garcia-Ceballos et al. (2018).
3	LCA + Sustainability Tool	Service life prediction models and LCA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI); Genetic Algorithm, Eco-indicator, SimaPro 5.0 [34] and BEET; EnergyPlus, GAOT, LCA, pre-use phase - Idemat2001 database, Ecoinvent1.2 database, Ecological Footprint (EF) and Environmental Priority Strategy (EPS2000), Economic Input Output LCA, and a process-based model, ATHENA, Impact Estimator, US life cycle inventory (US LCI) database, BIM (Revit) enhanced LCA methodology, Green Building Studio (GBS) and ATHENA Impact Estimator, SimaPro v8.0.1, Cumulative Energy Demand (CED) v1.08; and International Reference Life Cycle Data System (ILCD 2011) v1.03, midpoint method, Ecoinvent 2.2 .	Garcia-Ceballos et al. (2018), Grant and Ries (2013), Pushkar et al. (2005), Blengini (2009), Blengini and Di Carlo (2010), Srinivasan et al. (2014), Ajayi et al. (2015), Sosa et al. (2017), Evangelista et al. (2018), Himpe et al. (2013). .

Table A-4 Research methods and tools used for life cycle energy estimation (contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
4	LCE analysis	Life cycle energy analysis (LCEA), LCEA and life cycle GHG analysis (LCGA), e-Quest, energy simulation software.	Berggren et al. (2013), Atmaca and Atmaca (2015), Stephan et al. (2017), Kua and Wong (2012), Aneesh et al. (2018), Treloar et al. (2000).
5	Mathematical tools/calculations	Statistical analysis, Delphic Consultation Approach, Best-Worst multi-criteria decision method, sensitivity assessment, machine learning method, uncertainty-based design methods, Analytical Hierarchy Process (AHP), Arithmetic calculations and Swedish computer program Enorm, CAD and simulation tools, analytic network process (ANP), new quantitative approach energy–time consumption index (ETI), Multi-objective optimization based on - harmony search algorithm (HS), industrial survey. energy bills, field data-number of electrical fixtures and the duration of operation, multi-objective optimization using Strength Pareto Evolutionary Algorithm (SPEA2), Dependency Structure Modelling Value Bucket (DSM VB) algorithm, regression line using least squares method, chi-square test.	Pastore and Andersen (2019), Nii et al. (2017), Gupta et al. (2017), Song et al. (2017), Papadopoulos and Kontokosta (2019), Huang et al. (2018), Kanagaraj and Mahalingam (2011), Adalberth (1997a), Adalberth (1997b), O'Sullivan et al. (2004), Chen et al. (2006), Fesanghary et al. (2012), Praseeda et al. (2016), Taghizade et al. (2019), Lamé et al. (2017), Szalay (2008).

Table A-4 Research methods and tools used for life cycle energy estimation (contd…)

	Method category	**Research methodology/ Mathematical tool used**	**Author reference**
6	Proposed framework/ models	LC carbon dioxide emissions evaluation system and an environmental cost calculation method, mixed-mode building energy model, Benchmarking for life cycle costs and LCA, decision support tool, framework for the Energy Toolkit, integrated, life-cycle oriented design tool (LEGOE), accelerated buildings construction method with monolithic frame, building construction simulation using the software Lira, quantitative descriptive methodology, interdisciplinary approach, extended lifecycle building energy rating method, integrated design approach compliance modelling, Lesosais 5 for energy demand calculation, Polysuns 3.3 to calculate energy produced by solar collectors. PVsysts 3.21 to calculate electricity production by PV panels. life cycle impacts analysis (LCIA), holistic approach, metabolic network approach, Building Carbon Footprint (BCF) evaluation method, China building floor space estimation models (CBFSEM), life cycle sustainability assessment (LCSA) framework, housing stock management.	Chou and Yeh (2015), Xu and Shengwei (2008), König and De Cristofaro (2012), Horsley et al. (2003), Kohler and Lützkendorf (2002), Kiyanets (2016), Alawneh et al. (2018), Georgiadou et al. (2012), Hernandez and Kenny (2011), Li et al. (2014), Bros-Williamson et al. (2016), Citherlet and Defaux (2007), Danish et al. (2019), Yi et al. (2017), Liu (2019), Huo et al. (2019), (Onat et al., 2014a), Thomsen and van der Flier (2009).
7	Proprietary tools	LCA Inventory Tool v2.01 from CIT Ekologik in Sweden, Impact assessment method- equivalence factors from the CML and EDIP LCA methods, Allocation method- Post-Construction Audit (PCA) and Post-Occupancy Evaluation (POE), CfSH –environmental assessment tool (UK), Methodological triangulation, Parametric LCA model in Grasshopper3D, DIN V 18599 (2011), BIM enabled LCA, eBalance software and Chinese Life Cycle Database.	Schmidt et al. (2004), Georgiadou et al. (2013), Hollberg and Ruth (2016).

APPENDIX B: MATERIAL AND EE COEFFICIENTS OF SUB-SYSTEMS

Appendix B refers to Chapter 4 Pre-occupation stage. Tables B-1 to B-11 of Appendix B show the hierarchical level of material in each sub-system, EE coefficients of materials and unique sectoral energy of material production process.

Abbreviations used in the Appendix:

ECm - Embodied energy coefficient of material, Unique Sectoral Energy - Unique sectoral energy contribution to construction sector, I-O Table- Input-Output Table, MS-Mild Steel, PVC-Polyvinyl Chloride, CPVC-Chlorinated, PVC, UPVC- Unplasticised PVC, PCC- Plain cement concrete, RCC- Reinforced cement concrete, MDF- Medium density fibreboard, CI-Cast iron, GI-Galvanised iron, HT/LT-High tension/Low-tension, Elect-Electrical, HT/LT-High tension/Low tension, DG-Diesel generator.

Table B-1 Material and EE coefficients residential towers sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Structure						
	Columns, beams, slabs	Reinforcement steel	ton	38.000	17.26191	79-Iron and steel foundries
	Foundation and floor-levelling course	PCC & lean concrete	m^3	2.090	0.81642	76-Other non-metallic mineral products.
	Columns, beams, slabs	RCC	m^3	2.090		76-Other non-metallic mineral products.
Half brickwork	Walls	Bricks	m^2	0.220	0.55969	74-Structural clay products
	Cement mortar	Cement	ton	6.400	7.11089	75-Cement
Full brickwork	Walls	Bricks	m^2	0.220		74-Structural clay products
	Cement mortar	Cement	ton	6.400		75-Cement
MS structural works	Kitchen, toilet, staircase and balcony-counters, railing etc	Steel	ton	38.000		79-Iron and steel foundries

Table B-1 Material and EE coefficients residential towers sub-system (Contd…)

Element group	**Item / Element**	**Material**	**Unit**	**Embodied Energy Coefficient (GJ/Unit) (ECm)**	**Unique Sectoral Energy (TERm) (GJ/Rs lakhs)**	**I-O Table Sector**
Plastering	Internal and external walls, columns, ceiling	cement	ton	6.400		75-Cement
Flooring	kitchen, toilets, balcony flooring	Tiles-Vitrified / Ceramic	m^2	0..198		74-Structural clay products
	Kitchen platform, dining, living rooms flooring	Marble Stone	ton	16.610		76-Other non-metallic mineral products.
	Staircase-treads, landing, skirting	Kota Stone	ton	16.610		76-Other non-metallic mineral products.
	All floors PCC flooring	PCC	m^3	2.090		76-Other non-metallic mineral products.
	Wooden laminated flooring in Bedrooms	Laminated Timber	m^3	27.180	0.00877	56-Wood and wood products
Door, Windows	Doors- Main door, Internal bedroom, kitchen/ toilet	MDF/Plywood flush doors	m^3	18.000		56-Wood and wood products
	Door hardware	Stainless steel	ton	180.597	2.39139	77-Iron and steel ferro alloys
	Fire Door in Fire staircase	MS Sheet	ton	38.000		79-Iron and steel foundries
	MS door for staircase	MS Sheet	ton	38.000		79-Iron and steel foundries
	Aluminium doors, fixed glazing-Entrance Lobby	Aluminium Frame	ton	310.000	0.00052	80-Non-ferrous basic metals (including alloys)
		Glass toughened 6mm, 12 mm	ton	17.000		76-Other non-metallic mineral products.
	UPVC Windows	UPVC in frame	ton	61.000	0.28014	62-Plastic products
		Float Glass 5 mm, 6 mm, 8 mm thick	ton	17.000		76-Other non-metallic mineral products.
	PVC conduits 20-32 mm for concealed wiring	PVC	ton	55.000		62-Plastic products

Table B-1 Material and EE coefficients residential towers sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Paint works	Paint Works on Walls, ceiling, MS structural works-railings etc	Synthetic enamel paint	ton	144.000	0.22593	69-Paints, varnishes and lacquers
		Exterior paint	ton	144.000		69-Paints, varnishes and lacquers
		Acrylic Emulsion paint	ton	144.000		69-Paints, varnishes and lacquers
		Putty	ton	10.320		69-Paints, varnishes and lacquers
Interior works	False ceiling bedrooms	Gypboard	m^2	0.120		56-Wood and wood products
	Mirror in toilets	Float glass mirrors 6mm thick	ton	17.000		76-Other non-metallic mineral products.
	Tiling on roofs, floors, parapets, balcony projections	Cement concrete tiles	ton	13.000		76-Other non-metallic mineral products.
Internal plumbing	Sanitaryware fixtures-in toilets	Sanitaryware	ton	37.900		76-Other non-metallic mineral products.
	Kitchen sink	Stainless steel	ton	180.597		77-Iron and steel ferro alloys
	UPVC Soil, Waste, Vent & Rainwater (SWR) Pipes	UPVC	ton	61.000		62-Plastic products
	M.S. structural work for Sanitary fixtures and SWR Pipes	Steel	ton	38.000		79-Iron and steel foundries
	Cast Iron (CI) pipes-Soil, waste and vent pipes	Cast Iron	ton	38.000	0.00266	78-Iron and steel casting and forgings
	M.S. structural work for CI Pipes	Steel	ton	38.000		79-Iron and steel foundries

Table B-1 Material and EE coefficients residential towers sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Internal water supply-tower	Galvanised Iron (GI) Pipes 15 to 100 mm	Steel	ton	38.000		79-Iron and steel foundries
	Brass ball valve	Brass	ton	203.330		80-Non-ferrous basic metals (including alloys)
	CPVC Pipes 15 to 40 mm	CPVC	ton	61.000		62-Plastic products
	MS structural work for pipe supports, MS ladder etc.	Steel	ton	38.000		79-Iron and steel foundries
	Gunmetal pressure reducing valve	Gunmetal	ton	233.150		80-Non-ferrous basic metals (including alloys)

ECm - Embodied energy coefficient of material, Unique Sectoral Energy - Unique sectoral energy contribution to construction sector, I-O Table- Input-Output Table, MS-Mild Steel, CPVC-Chlorinated PVC, PVC-Polyvinyl Chlorid

Table B-2 Material and EE coefficients external water supply sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Structure - Pump house & water Tanks	Columns, beams, slabs	Reinforcement steel	ton	38.000	17.26191	79-Iron and steel foundries
	Foundation and floor-levelling course	PCC & lean concrete	m^3	2.090	0.81642	76-Other non-metallic mineral products.
	Columns, beams, slabs	RCC	m^3	2.090		76-Other non-metallic mineral products.
Full brickwork	Walls	Bricks	m^2	0.220	0.55969	74-Structural clay products
	Cement mortar	Cement	ton	6.400	7.11089	75-Cement
Plastering	Internal and external walls, columns	Cement	ton	6.400		75-Cement
Flooring	PCC Flooring - 75 mm thick	PCC	m^3	2.090		76-Other non-metallic mineral products.
Door	Fire Door in Pump Rooms	Steel in MS Sheet	ton	38.000		79-Iron and steel foundries
	MS doors in Plumbing shaft	Steel in MS Sheet	ton	38.000		79-Iron and steel foundries
Pumps and WTP						
Water pumps	Pumps-various sizes	Pumps-various sizes	Rs Lakhs	96.754	0.00138	87-Other non-electrical machinery
Water Treatment Plant (WTP)	Water Treatment Plant (WTP)	Strainers, filters, water softener and chlorine dozer etc	Rs Lakhs	19.896	0.02490	108-Water supply

Table B-2 Material and EE coefficients external water supply sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Plumbing						
Pipe connections	MS Pipe connections	Steel	ton	38.000		79-Iron and steel foundries
Plumbing - domestic line, borewell line, municipality water connections	UPVC agricultural pipes 20 to 110 mm	UPVC	ton	61.000	0.28014	62-Plastic products
	C.I. LA Pipes 100 mm	Steel	ton	38.000	0.00266	78-Iron and steel casting and forgings
Plumbing Flushing Line	UPVC agricultural pipes 20 to 110 mm	UPVC	ton	61.000		62-Plastic products

Table B-3 Material and EE coefficients external electric supply sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Substation equipment						
	Transformers, HT/LT Panels, DG Sets	Transformers, HT/ LT Panels, DG Sets	Rs Lakhs	52.684	0.00015	88-Electrical industrial machinery
	Conductors	Feeders, HT/LT cables	Rs Lakhs	56.471	0.14045	89-Electrical wires & cables
Structure-Power house, elect rooms	**Elect Shaft, LV Shaft**					
	Columns, beams, slabs	Reinforcement Steel	ton	38.000	17.26191	79-Iron and steel foundries
	Foundation	PCC	m^3	2.090	0.81642	76-Other non-metallic mineral products.
	Columns, beams, slabs	RCC	m^3	2.090		76-Other non-metallic mineral products.
Walls	Brickwork	Bricks	m^2	0.220	0.55969	74-Structural clay products
		Cement	ton	6.400	7.11089	75-Cement
Floor	PCC Flooring	PCC	m^3	2.090		76-Other non-metallic mineral products.
Doors	MS doors in LV, FTTH, Elect rooms	Steel in MS Sheet	ton	38.000		79-Iron and steel foundries
	Fire door in Substation, Elect Shaft	Steel in MS Sheet	ton	38.000		79-Iron and steel foundries
Plaster	Walls, columns, ceiling	Cement	ton	6.400		75-Cement

Elect-Electrical, HT/LT-High tension/Low tension, DG-Diesel generator,

Table B-4 Material and EE coefficients sewage treatment plant (STP) sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Structure STP						
	Columns, beams, slabs	Steel Reinforcement	ton	38.000	17.26191	79-Iron and steel foundries
	Footings, Bases for Columns, Plinth Beam, Floor	PCC	m^3	2.090	0.81642	76-Other non-metallic mineral products.
	Foundation, Footing, Beams Columns, Slabs, Wall, Staircase	RCC	m^3	2.090		76-Other non-metallic mineral products.
	MS structural work	Steel	ton	38.000		79-Iron and steel foundries
Pumps	Pumps various sizes	Pumps various sizes	Rs Lakhs	96.754	0.00138	87-Other non-electrical machinery
STP	STP 750 KLD - Sequential Batch Reactor		Rs Lakhs	26.76448	0.00229	129-Other services
Sewerage line	RCC pipe-200, 250, 400 mm		Rs Lakhs	42.990		76-Other non-metallic mineral products.
	Bed concrete /haunches	PCC	m^3	2.090		76-Other non-metallic mineral products.
	C.I. LA Pipes 150 mm - (From STP)	Steel	ton	38.000	0.00266	78-Iron and steel casting and forgings

STP-Sewage treatment plant

Table B-5 Material and EE coefficients vehicle parking sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Structure Basement	M&L Reinforcement Steel	Reinforcement Stee	ton	38.000	17.26191	79-Iron and steel foundries
	PCC & lean concrete	PCC	m^3	2.090	0.81642	76-Other non-metallic mineral products.
	RCC	RCC	m^3	2.090		
	Brickwork I-Class in CM 1:6	Bricks	m^2	0.220	0.55969	74-Structural clay products
		Cement	ton	6.400	7.11089	75-Cement
	Plastering - Walls, Columns and Ceiling	Cement	ton	6.400		
	Basement Synthetic enamel paint	Synthetic enamel paint	ton	144.000	0.22593	69-Paints, varnishes and lacquers
	Basement floor and Ramp- PCC 75 mm thick	PCC	m^3	2.090		
Basement plumbing	MS Pipes 80 t0 100 mm, MS Structural Works, GI Pipes 15 to 100 mm	Steel	ton	38.000		
	Cast Iron Pipes 75 to 150 mm	Steel	ton	38.000	0.00266	78-Iron and steel casting and forgings

Table B-5 Material and EE coefficients vehicle parking sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Concrete pavers in parking	PCC in Road/pathways	PCC	m^3	2.090		
	granite stone	Granite stone	ton	18.093	0.17215	**37-Other non-metallic minerals**
	Dholpur stone (Sand Stone)	Sand stone	ton	0.864		
	Concrete Pavers 80 mm thick	PCC	m^3	2.090		
Internal Elect - Basement Parking	Light Fixtures	Light Fixtures	Rs Lakhs	41.903	0.00168	**91-Electrical appliances**
	Elect Wiring	Elect Wiring	Rs Lakhs	56.471	0.14045	**89-Electrical wires & cables**
	PVC Conduits in wall 20 to 40 mm	PVC	ton	55.000	0.28014	**62-Plastic products**

Table B-6 Material and EE coefficients HVAC sub-system

Element group	Element / Item	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Refrigerant piping.	Copper tubes in ceiling, wall 6 mm, 9 mm, 12 mm	Copper	ton	90.000	0.000523306	**080-Non-ferrous basic metals (including alloys)**
Power and control wiring	Power and control wiring in conduits in wall/ floor-4 C X 2.5 Sq mm	Wiring/Cables	Rs Lakhs	56.471	0.140449464	**089-Electrical cables, wires**
Split type air-conditioning (AC)	Split Air Conditioners (ACs)-wall mounted-various sizes	Split Air Conditioners	Rs Lakhs	96.754	0.001378906	**087-Other non-electrical machinery**
Insulated Drain Piping	UPVC piping (in wall/floor) - 20 mm	UPVC	ton	61.000	0.280144113	**62-Plastic products**

Table B-7 Material and EE coefficients elevators sub-system

Element group	**Item / Element**	**Material**	**Unit**	**Embodied Energy Coefficient (GJ/Unit) (ECm)**	**Unique Sectoral Energy (TERm) (GJ/Rs lakhs)**	**I-O Table Sector**
Elevators	Passenger Lifts & Service Lifts	Fabricated material	Rs Lakhs	96.75	0.00138	**087 Other non-electrical machinery**
Structure	Columns, beams, slabs	Reinforcement Steel	ton	38.00	17.26191	**79-Iron and steel foundries**
	Foundation and flooring	PCC & lean concrete-	m^3	2.090	0.81642	**76-Other non-metallic mineral products.**
	Columns, beams, slabs	RCC	m^3	2.090		
Walls	Brickwork	Bricks	m^2	0.220	0.55969	**74-Structural clay products**
	Cement mortar	Cement	ton	6.40	7.11089	**75-Cement**
Plaster	Plastering-Walls & Columns -12 mm	Cement	ton	6.40		
	Plastering Ceiling 6 mm	Cement	ton	6.40		
Flooring	Marble Stone in Lift & Lift Lobby	Marble Stone	ton	16.61		
Doors	MS Fire doors	Steel in MS Sheets	ton	38.00		
Interior work						
False ceiling	Gypboard false ceiling Lift lobby	Gypboard	m^2	0.12	0.00877	**56-Wood and wood products**
Paint Work	Acrylic Emulsion paint in Lift Lobby	Acrylic Emulsion paint	ton	144.000	0.22593	**69-Paints, varnishes and lacquers**

Table B-8 Material and EE coefficients firefighting (FF) sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Firefighting & Detection Equipment	Fire pumps various sizes	Fire Pumps	Rs Lakhs	96.75	0.00138	**87-Other non-electrical machinery**
Fire Pumps Accessories & fixing	MS pipes 25 to 400 mm	Steel	ton	38.00	17.26191	**79-Iron and steel foundries**
	MS Structural Works	Steel	ton	38.00		
	Hand appliances tower & basement	Hand appliances	Rs Lakhs	96.75		**87-Other non-electrical machinery**
	Fire detection system, Fire alarm (Towers)	Electronic panels, communication system	Rs Lakhs	26.15	0.00176	**94-Electronic equipment Sector**
	Electrical cables	Electrical cables	Rs Lakhs	56.47	0.14045	**89-Electrical cables, wires**
Structure	Fire tanks, fire hose cabinet	Reinforcement Steel	ton	38.00		**79-Iron and steel foundries**
		PCC	m^3	2.09	0.81642	**76-Other non-metallic mineral products.**
		RCC	m^3	2.09		
Brickwork	Half Brickwork	Bricks	m^2	0.22	0.55969	**74-Structural clay products**
		Cement	ton	6.40	7.11089	**75-Cement**
Plaster	Plaster in walls, ceiling	Cement	ton	6.40		
Paint	Synthetic enamel paint	Synthetic enamel paint	ton	144.00	0.225928	**69-Paints, varnishes and lacquers**
Flooring	Flooring - PCC 75 mm thick	PCC	m^3	2.09		

Table B-8 Material and EE coefficients firefighting (FF) sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Fire hydrant internal & external	MS pipes 25 to 150 mm	Steel	ton	38.00		
	MS Structural works	Steel	ton	38.00		
Sprinkler system tower & basement	MS pipes 25 to 150 mm	Steel	ton	38.00		
	MS Structural works	Steel	ton	38.00		

Table B-9 Material and EE coefficients site development features sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Boundary wall, Guard room, Meter room etc	PCC & lean concrete	PCC	m^3	2.090	0.81642	**76-Other non-metallic mineral products.**
	Full brickwork	Bricks	m^2	0.220	0.55969	**74-Structural clay products**
		Cement	ton	6.400	7.11089	**75-Cement**
	Half brickwork	Bricks	m^2	0.220		
		Cement	ton	6.400		
	Plastering in walls/ columns	Cement	ton	6.400		
	RCC In foundation /footing, columns & walls	RCC	m^3	2.090		
	Reinforcement steel in footing, columns, pillars	Steel	ton	38.000	17.26191	**79-Iron and steel foundries**
	MS Railing in boundary wall	Steel	ton	38.000		
	MS Structural Work	Steel	ton	38.000		
	MS Angle -Y Shaped frame in boundary wall fencing	Steel	ton	38.000		
	GI Concertina coil in boundary wall fencing	Steel	ton	38.000		

Table B-9 Material and EE coefficients site development features sub-system (Contd…)

Element group	**Item / Element**	**Material**	**Unit**	**Embodied Energy Coefficient (GJ/Unit) (ECm)**	**Unique Sectoral Energy (TERm) (GJ/Rs lakhs)**	**I-O Table Sector**
	Painting					
	Exterior paint on boundary wall and other external areas	Exterior paint	ton	144.000	0.22593	**69-Paints, varnishes and lacquers**
	Synthetic enamel paint, on MS Railing -Boundary Wall	Synthetic enamel paint	ton	144.000		**69-Paints, varnishes and lacquers**
Main gate	MS Main gate	Steel	ton	38.000		
Security-Access control system	Vehicle tag scanner, CCTV Camera, LCD monitor etc	Access control hardware & software	Rs Lakhs	26.148	0.00176	**94-Electronic equipment including TV**
	Intercom equipment-telephone sets,	Intercom equipment	Rs Lakhs	23.610	0.00000	**92-Communication equipment**
	UPS for control room, boom barriers	UPS	Rs Lakhs	60.534	0.00001	**93-Other electrical machinery**
	Cabling various sizes	Electric cables	Rs Lakhs	56.471	0.14045	**89-Electrical wires & cables**
	PVC Conduiting for data and power supply	PVC	ton	55.000	0.28014	**62-Plastic Products**

Table B-9 Material and EE coefficients site development features sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Approach road and PCC Block Pavement	GSB, WMM, DBM, Bituminous Concrete	Aggregate	ton	0.110	0.17215	**37-Other non-metallic minerals**
	DBM, Bituminous Concrete	Bitumen	ton	13.716	0.13861	**63-Petroleum products**
	Tack coat, primer coat	Bitumen emulsion	ton	9.601		**63-Petroleum products**
	Paver Blocks	PCC	m^3	2.090		
	RCC Pipes	Reinforcement Steel	ton	38.000		
	RCC Pipes	RCC	m^3	2.090		
Internal road, pathways, Area pavement	WMM 225 mm thick	Aggregate	ton	0.110		
	GSB 200 mm thick	Aggregate	ton	0.110		
	Brickwork in toe wall	Brick	m^2	0.220		
		Cement	ton	6.400		
	Granite stone work in Cement mortar	Granite Stone	ton	18.093		**37-Other non-metallic minerals**
		Cement in cement mortar	ton	6.400		
	RCC in railing	RCC	m^3	2.090		
	Dholpur stone work in Cement mortar	Sand Stone	ton	0.864		**37-Other non-metallic minerals**
		Cement in cement mortar	ton	6.400		

GSB- Granulated sub base, WMM- Wet mix macadam, DBM- Dense bituminous macadam

Table B-9 Material and EE coefficients site development features sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Street lighting/ Area lighting	Light Fixtures	Light fixtures	Rs Lakhs	41.903	0.00168	**91-Electrical appliances**
	Wiring & cables various sizes	Wiring/cable	Rs Lakhs	56.471	0.14045	**89-Electrical wires & cables**
	Elect accessories	Elect accessories	Rs Lakhs	60.534	0.00001	**93-Other electrical machinery**
	HDPE Pipes-50 to 150 mm	HDPE	ton	55.000	0.28014	**62-Plastic products**
	PVC Pipes 25 to 100 mm	PVC	ton	55.000		**62-Plastic products**
	GI Wire	Steel	ton	38.000		
	MS/GI Electric Poles	Steel	ton	38.000		
Rain water harvesting system	UPVC Pipe perforated	UPVC	ton	61.000		**62-Plastic products**

Table B-9 Material and EE coefficients site development features sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Storm drainage & sub soil drainage	RCC pipe for pipe culvert- 200, 250, 400 mm	RCC	m^3	2.090		
		Reinforcement Steel	ton	38.000		
	PCC in haunches of RCC pipes and bed concrete	PCC mm	m^3	2.090		
	UPVC Pipe 150 mm	UPVC	ton	61.000		
	Drain Cover	Steel	ton	38.000		
	MS pipes 100 mm for sub-soil drainage	Steel	ton	38.000		

Table B-10 Material and EE coefficients sports facilities sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Structure Swim Pool	Reinforcement Steel	Steel	ton	38.000	17.26191	**79-Iron and steel foundries**
	PCC & lean concrete	PCC	m^3	2.090	0.81642	**76-Other non-metallic mineral products.**
	RCC in Foundation, raft and base of water bodies	RCC	m^3	2.090		
	RCC in Foundation/ Walls	RCC	m^3	2.090		
	Half Brickwork	Bricks	m^2	0.220	0.55969	**74-Structural clay products**
		Cement	ton	6.400	7.11089	**75-Cement**
	Full Brickwork	Bricks	m^2	0.220		
		Cement	ton	6.400		
	Ceramic Tile	Ceramic Tile	ton	8.200		
	Granite stone work in Floor	Granite	ton	18.093		**76-Other non-metallic mineral products.**
	Plaster	Cement	ton	6.400		

Table B-10: Material and EE coefficients sports facilities sub-system (Contd…)

Element group	**Item / Element**	**Material**	**Unit**	**Embodied Energy Coefficient (GJ/Unit) (ECm)**	**Unique Sectoral Energy (TERm) (GJ/Rs lakhs)**	**I-O Table Sector**
Swim pool plumbing & water treatment, electrical works/ lighting	**Recirculation Pumps-** Various sizes 8 Nos	Recirculation Pumps	Rs Lakhs	96.754	0.00138	**87-Other non-electrical machinery**
	Elect panel, Transformer for lights	Electric panel, Transformer	Rs Lakhs	52.684	0.00015	**88-Electrical industrial machinery**
	Power cables various sizes	Power cables	Rs Lakhs	56.471	0.14045	**89-Electrical wires & cables**
	Underwater Illumination	LED lighting	Rs Lakhs	41.903	0.00168	**91-Electrical appliances**
	UPVC Pipes with fittings 63-200 mm	UPVC	ton	61.000	0.28014	**62-Plastic products**
	M.S. structural work - for pipe supports, clamps, MS ladder, manhole tank covers etc.	Steel	ton	38.000		
	MS Pipes	Steel	ton	38.000		

Table B-10: Material and EE coefficients sports facilities sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Tennis courts, Gym						
Court	Water bound macadam (WBM)	Aggregate	ton	0.110		**76-Other non-metallic mineral products.**
	Bituminous macadam course (Bitumen @1.5 % by weight)	Bitumen	ton	44.700	0.13861	**63-Petroleum products**
		Aggregate	ton	0.220		
	Asphalt concrete 20 mm thick (Bitumen @2.0 % by weight)	Bitumen	ton	13.716		
		Aggregate	ton	0.110		
Fencing	MS Poles	Steel	ton	38.000		
	Wire mesh	Steel	ton	38.000		
	Base Concrete PCC	PCC	m^3	2.090		
Lights	Tennis court lights	Light fittings	Rs Lakhs	41.903		**91-Electrical appliances**
	Gym equipment	Gym Equipment	Rs Lakhs	40.644	0.09933	**105-Miscellaneous manufacturing**

Table B-11 Material and EE coefficients site beautification features sub-system

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Arboriculture/ Soft landscaping						
Garden irrigation system	UPVC Agricultural pipes 25 to 90 mm	UPVC	ton	61.000	0.28014	**62-Plastic products**
Miscellaneous Items						
	Music system works at garden area		Rs Lakhs	26.148	0.00176	**94-Electronic equipment(incl.TV)**
	Grill pine cone	Fibre glass Reinforced Concrete	Rs Lakhs	42.990	0.81642	**76-Other non-metallic mineral products.**
Lawn, outdoor seating	PCC to create levels & slopes	PCC	m^3	2.090		
	Brickwork	Bricks	m^2	0.220	0.55969	**74-Structural clay products**
		Cement	ton	6.400	7.11089	**75-Cement**
Wafer bodies-Structure	PCC in foundation	PCC	m^3	2.090		
	RCC in foundation and walls	RCC	m^3	2.090		
	Reinforcement in RCC work in foundation & walls	Steel	ton	38.000	17.26191	**79-Iron and steel foundries**
	Half Brickwork	Bricks	m^2	0.220		
		Cement	ton	6.400		
	Ceramic tile in floors, walls	Ceramic tile	ton	8.200		
	Granite stone water trough	Granite stone	ton	18.093	0.17215	**37-Other non-metallic minerals**
	Cement in CM	Cement	ton	6.400		

Table B-11 Material and EE coefficients site beautification features sub-system (Contd…)

Element group	Item / Element	Material	Unit	Embodied Energy Coefficient (GJ/Unit) (ECm)	Unique Sectoral Energy (TERm) (GJ/Rs lakhs)	I-O Table Sector
Water bodies - filtration, pumps, plumbing, lighting	Water Pumps various sizes	Water Pumps	Rs Lakhs	96.754	0.00138	**87-Other non-electrical machinery**
	Water Purification system	Water Purification - Pressure Sand filter, Chemical Doser	Rs Lakhs	19.896	0.02490	**108-Water supply**
	Lighting fixtures	Lighting fixtures	Rs Lakhs	41.903	0.00168	**91-Electrical appliances**
	UPVC Pipes various sizes	UPVC	ton	61.000		**62-Plastic products**
	MS Structural Work	Steel	ton	38.000		
	MS Pipes various sizes	Steel	ton	38.000		
	Elect Panel 415 V	Elect Panel	Rs Lakhs	52.684	0.00015	**88-Electrical industrial machinery**
	Elect cables	Elect cables	Rs Lakhs	56.471	0.14045	**89-Electrical wires & cables**
Garden Sitout	RCC in foundation	RCC	m^3	2.090		
	Steel reinforcement in foundation	Steel	ton	38.000		
	MS Tubular frames for columns	Steel	ton	38.000		
	Timber various sizes	Timber	m^3	22.901	0.00877	**56-Wood and wood products**

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS

Building material / ↓ Life span (years) →	Ghaemi and Amidpour (2019)	Marsh (2016)	Iddon and Firth (2013)	Ding (2007)	Adalberth (1997a)	Scheuer et al. (2003)	Chau et al. (2007)	Life span considered for current study	Reference for current study
Reinforcement steel	50	120	-	-	-	75	50	120	Marsh (2016)
Cement concrete (RCC/PCC)	-	120	120	-	-	75	50	120	Marsh (2016)
Structural steel	-	-	-	-	-	75	50	50	Chau et al. (2007)
Structural timber	-	120	-	-	-	-	-	120	Marsh (2016)
Brick	60	-	120	60	-	-	50	50	Chau et al. (2007)
Roof tile	-	-	60	30	30	-	-	60	Iddon and Firth (2013)
Floor tiles-ceramic	60	-	60	-	-	75	10	60	Ghaemi and Amidpour (2019
Cement plaster									
Internal-walls, ceiling								25	Janjua et al. (2019)
External walls								15	Janjua et al. (2019)
Flooring									
Marble Flooring						75		75	Scheuer et al. (2003)
Kota stone/ Dholpur stone/ Sand stone						75		75	Scheuer et al. (2003)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material / ↓	Life span (years) →	Ghaemi and Amidpour (2019)	Marsh (2016)	Iddon and Firth (2013)	Scheuer et al. (2003)	Chau et al. (2007)	Hong et al. (2009)	NAHB (2007)	Life span considered for current study	Reference for current study
Granite stone					75				75	Scheuer et al. (2003)
PCC flooring			120						120	Marsh (2016)
PCC tiles									60	Assumed same as for ceramic Tiles Chau et al. (2007)
Timber & Wood Products										
Laminated wooden flooring								50	50	NAHB (2007)
Gypboard false ceiling bedrooms, lift lobby					75				50	Saint Gobain (2016)
Precast reinforced concrete balustrades									120	Taken same as RCC Marsh (2016)
Wooden flush doors (MDF/plywood)								50	50	NAHB (2007)
Metal doors-MS sheet in MS doors, Fire doors					50				50	Scheuer et al. (2003)
Aluminium door frame					50				50	Scheuer et al. (2003)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	Marsh (2016)	Iddon and Firth (2013)	Ding (2007)	Scheuer et al. (2003)	Chau et al. (2007)	UWDMA (2016)	CPWD (2019)	DOHACD (2017)	NAHB (2007)	Life span considered for current study	Reference for current study
UPVC window frames					50		50				50	UWDMA (2016)
Window glazing							25				25	UWDMA (2016)
Glazing gaskets and weather seals							15				15	UWDMA (2016)
PVC conduit pipes					50						50	Scheuer et al. (2003)
Paints												
Synthetic enamel paint		15	5	10	5	10		3			5	Scheuer et al. (2003)
Exterior paint (Silicon based)								5	10	15	5	CPWD (2019)
Internal-Acrylic emulsion paint,								3	7	15	3	CPWD (2019)
Whitewash/ colourwash								2			2	CPWD (2019)
Glass & glass products												
Float glass mirror		25									25	Assumed same as glass Marsh (2016)
Sanitary fixtures					50				20		20	DOHACD (2017)
Stainless steel sink					50						50	Scheuer et al. (2003)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	Marsh (2016)	Iddon and Firth (2013)	Ding (2007)	Scheuer et al. (2003)	Chau et al. (2007)	Parvez (2018)	CPWD (2019)	DOHACD (2017)	NAHB (2007)	Life span considered for current study	Reference for current study
Plumbing items												
UPVC water pipes							100				100	Parvez (2018)
HDPE pipes							50				50	Parvez (2018)
UPVC SWR pipes							50				50	Parvez (2018)
CPVC pipes											50	Hakansson et al. (2013)
MS pipes					50						50	Scheuer et al. (2003)
CI pipes					50						50	Scheuer et al. (2003)
GI pipes					50						50	Scheuer et al. (2003)
Valves-brass/ gun metal										20	20	NAHB (2007)
Conduit wiring								20			20	CPWD (2019)
Ceiling fan								20			20	CPWD (2019)
Light fittings									15-20		20	DOHACD (2017)
Electrical fixtures									15-20		20	DOHACD (2017)
Waterproofing												
Roof								10			10	CPWD (2019)
Water tanks/ Fire tanks											10	Assumed
Swimming pool											10	Assumed

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	Marsh (2016)	Ding (2007)	Adalberth (1997a)	Scheuer et al. (2003)	Chau et al. (2007)	CPWD (2019)	ATO (2020)	Life span considered for current study	Reference for current study
Firefighting										
Fire pumps								25	25	ATO (2020)
MS Structural works					75	50			50	Chau et al. (2007)
Fire hydrant system (Internal)									50	Assumed
Sprinkler system for tower & basement									50	Assumed
Hand appliances (Firefighting)								15	15	ATO (2020)
Fire Detection, Alarm System,										
Electronic panels, communication system								12	12	ATO (2020)
Fire tanks									120	Taken same as RCC
Fire hoses								10	10	ATO (2020)
Fire hose cabinet									50	Assumed
Site Development features										
MS railing in boundary wall						50			50	Chau et al. (2007)
MS Angle -Y Shaped in Wall Fencing						50			50	Chau et al. (2007)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓ Life span (years) →	Marsh (2016)	Ding (2007)	Scheuer et al. (2003)	Chau et al. (2007)	CPWD (2019)	ATO (2020)	Life span considered for current study	Reference for current study
GI concertina coil in boundary wall fencing						15	15	ATO (2020)
Access control hardware & software						5	5	ATO (2020)
Intercom Equipment								
UPS						15	15	ATO (2020)
Intercom equipment						12	12	ATO (2020)
Intercom cabling						12	12	Taken same as Intercom Eqpt
Road Work								
Carpeting/ resurfacing of roads					5		5	CPWD (2019)
Paver blocks 80 mm thick							50	Assumed same as PCC
RCC pipes			75				75	Scheuer et al. (2003)
PCC in road, Footpath							50	Assumed
Drain cover- (structural steel)				50			50	Chau et al. (2007)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	(Marsh, 2016)	Kirk and Dell'Isola (1995)	Scheuer et al. (2003)	CPHEEO (1999)	CPWD (2019)	Hong et al. (2009)	ATO (2020)	Life span considered for current study	Reference for current study
External Water Supply										
Electric pumps			20		15	10			10	CPWD (2019)
Water treatment plant			7		15			10	7	ATO (2020)
Filter media,			5					10	5	Kirk and Dell'Isola (1995)
External Electrification										
Transformers						25			25	CPWD (2019)
HT/ LT Panels/ Switchgear						20			20	CPWD (2019)
Diesel generator sets						15			15	CPWD (2019)
Feeders cable overhead						25			25	CPWD (2019)
HT/LT cables -UG						30			30	CPWD (2019)
Sewage Treatment Plant (STP)										
Pumps various sizes						10	15		10	CPWD (2019)

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	(Marsh, 2016)	Kirk and Dell'Isola (1995)	Scheuer et al. (2003)	CPHEEO (1999)	CPWD (2019)	Hong et al. (2009)	NAHB (2007)	Life span considered for current study	Reference for current study
Sewage Treatment Plant (STP)										
Pumps various sizes						10	15		10	CPWD (2019)
STP							7		7	Hong et al. (2009)
SWG pipe				75					75	Scheuer et al. (2003)
R.C.C pipe				75					75	Scheuer et al. (2003)
Parking										
Concrete pavers		120							120	Marsh (2016)
Polycrete tiles									25	UL Environment (2022)
Electrical wiring						20			20	CPWD (2019)
PVC conduits				50					50	Scheuer et al. (2003)
Exhaust fans						6			6	CPWD (2019)
Elevators				40		20			20	CPWD (2019)
Plywood (panelling etc)								30	30	NAHB (2007)

APPENDIX-C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓	Life span (years) →	Marsh (2016)	Ding (2007)	Scheuer et al. (2003)	Chau et al. (2007)	CPWD (2019)	NAHB (2007)	ATO (2020)	Others	Life span considered for current study	Reference for current study
Street lights/ Area lighting											
GI wire										25	Assumed
Electric poles -MS/GI				50						50	Scheuer et al. (2003)
Grasscrete pavers									50	50	(Grass Concrete Limited, 2021)
Underwater LED lighting, junction box										10	Assumed
Tennis court											
Synthetic acrylic surfaces									9	9	Tennis Australia (2021)
Steel in fencing MS poles				50						50	Scheuer et al. (2003)
Steel in fencing wire mesh								20		20	ATO (2020)
Tennis court lights										20	Assumed

APPENDIX C: EXPECTED LIFE SPAN OF BUILDING COMPONENTS (contd…)

Building material ↓ Life span (years) →	Marsh (2016)	Ding (2007)	Scheuer et al. (2003)	Chau et al. (2007)	CPWD (2019)	NAHB (2007)	ATO (2020)	Others	Life span considered for current study	Reference for current study
Gym equipment										
Treadmill								10	10	Home Gym Resource (2021)
Upright bike, elliptical trainer etc, bench press								20	20	(Home Gym Resource)
Dumbbell set								50	50	Assumed same as building life of 50 years)
Site beautification										
Music system works at garden area							7		7	ATO (2020)
Wooden planks			75						75	Scheuer et al. (2003)
HVAC										
Packaged type air conditioner					8				8	CPWD (2019)

APPENDIX D: REPLACEMENT FACTORS

This Appendix shows the replacement factor of material/components of each sub-system in **Tables D-1 to D-11**, cost elements for EE estimation on repair and maintenance in **Table D-12**, and cost elements for operating cost of common services in **Table D-13.**

Table D-1 Replacement factors residential towers sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement factor) (N) (Nos)	Remarks
Structure				
Plastering -walls & columns in cement mortar 1;6 (12 mm thick)	25	1	1	
Plastering -ceiling in cement mortar 1:3 (6 mm thick)	25	1	1	
External plaster tower elevation- 18 mm thick	15	3	2	Reduced No. of replacement by one since residual life after 2nd renewal is only 5 years
Water proofing of roof	10	4	4	
Doors and windows				
Aluminium doors, fixed glazing-entrance lobby				
Glass toughened	25	1	1	
Gaskets, fittings and weather seal	15	3	3	Replacement frequency not reduced due safety concerns
UPVC Windows with hardware				
Float Glass	25	1	1	
Gaskets, fittings and weather seal	15	3	3	Replacement frequency not reduced due safety concerns though residual life would be 5 years

Table D-1: Replacement factors residential towers sub-system (contd…)

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement factor) (N) (Nos)	Remarks
Painting works				
Synthetic enamel paint	5	9	9	
External surface paint	5	9	9	
Acrylic emulsion paint	3	16	15	Reduced No. of replacements by one since residual life after 15th renewal is only 2 years
Interior work				
Float glass / mirrors in toilets	25	1	1	
Sanitary fixtures				
EWC with P Trap, 'S' Trap, wash basin	20	2	2	
Internal water supply-tower				
Brass ball valve full bore type with lever	20	2	2	
Gunmetal pressure reducing valves	20	2	2	
Internal electrification	20	2	2	

Table D-2 Replacement factors external water supply sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement factor) (N) (Nos)	Remarks
Structure - external water supply				
Water proofing treatment	10	4	4	
Plastering -walls in cement mortar 1;6 (12 mm) (internal)	25	1	1	
Whitewash	2	24	24	
Internal electrification	20	2	2	
Pumps and WTP				
Pumps-various sizes	10	4	4	
MS pipes with MS fittings in brick work/ RCC 40-200 mm diameter (dia)	50	0	0	
Valves various sizes	20	2	2	
WTP-Water treatment eqpt, filter etc	7	7	6	
Plumbing domestic line, borewell line				
UPVC Agricultural pipes with all fittings 20 to 110 mm diameter	100	0	0	
C.I. LA Pipes 100 mm including lead jointing, fittings	50	0	0	
Valves, chambers	20	2	2	

Eqpt- Equipment

Table D-3 Replacement factors external electric supply sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement factor) (N) (Nos)	Remarks
Substation equipment & installation including diesel generator sets				
Transformers	25	1	1	
HT panels	20	2	2	
LT panels	20	2	2	
Diesel generator set	15	3	2	
33 KV Feeding lines from feeder 66 KV	25	1	1	
HT-LT Cables	30	1	1	
Structure - power house, electrical rooms, electrical shaft, LV shaft				
Water proofing,	10	4	4	
Plaster- Walls, columns in cement mortar 1:6 (12 mm thick)	25	1	1	
Plaster- Ceiling in cement mortar 1:3 (6 mm thick)	25	1	1	
Internal electrification	20	2	2	

Table D-4 Replacement factors sewage treatment plant (STP) sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Structure STP				
Reinforcement	120	0	0	
PCC & lean concrete- in footings etc	120	0	0	
RCC in foundation, beams etc	120	0	0	
Water proofing of structure	10	4	4	
M.S. structural work	50	0	0	
Pumps				
Pumps various sizes	10	4	4	
STP				
Sewage treatment plant	7	7	6	
Sewerage line				
SWG pipe-200, 250,300 mm	75	0	0	
Cement concrete 1:5:10 - bed concrete/haunches	120	0	0	
Manhole-brick masonry conical type- various diameter	60	0	0	
Providing and fixing C.I. LA pipes 150 mm - (From STP)	100	0	0	

Table D-5 Replacement factors vehicle parking sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated Nos of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Structure basement parking				
Reinforcement steel	120	0	0	
PCC & lean concrete	120	0	0	
RCC in all grades	120	0	0	
Water proofing treatment	10	4	4	
Brickwork I-Class in cement mortar 1:6	60	0	0	
Plastering - walls & columns in cement mortar 1;6 (12 mm thick)	25	1	1	
Plastering -ceiling in cement mortar 1:3 (6 mm thick)	25	1	1	
Basement synthetic enamel paint	5	9	9	
Basement floor -75 mm thick cement concrete flooring	120	0	0	
Ramp flooring -PCC 75 mm thick	120	0	0	
Concrete pavers in Parking	120	0	0	
Basement plumbing				
Soil, waste, vent & rain water pipes-MS pipes, CI pipes	50	0	0	
MS Structural works	50	0	0	
Internal electrification basement (parking)				
Light fixtures	20	2	2	
Electrical wiring	20	2	2	
PVC Conduit	50	0	0	

Table D-6 Replacement factors HVAC sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated Nos of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Refrigerant piping - copper tubing in ceiling / wall.				
Copper tubes 1/4", 1/2", 3/8"	20	2	2	
Power and control wiring in conduits in wall/ floor-4 Core X 2.5 Sq mm	20	2	2	
Split type air-conditioning (AC) system,				
Split air conditioners (ACs)-wall mounted- various sizes	10	4	4	
Insulated drain piping				
UPVC plumbing class piping (in wall/floor) - 20 mm diameter	100	0	0	

Table D-7 Replacement factors elevators sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Elevators				
Passenger lifts & service lifts	20	2	2	
Structure				
Reinforcement steel	120	0	0	
PCC & lean concrete-	120	0	0	
RCC in all grades	120	0	0	
Brickwork I-Class in cement mortar 1:6	60	0	0	
Plastering - wall, ceiling	25	1	1	
Flooring - marble stone in lift & lift lobby	100	0	0	
Doors & door frame-lift lobby	50	0	0	
Interior Work				
Gypboard false ceiling lift lobby	50	0	0	
POP in lift lobby	25	1	1	Assumed same as internal Plaster
Mirror panelling in lifts	25	1	1	
Veneer plywood panelling, Lifts	30	1	1	
Whitewash in lift well	2	24	24	
Acrylic emulsion paint in lift lobby	3	16	15	

Table D-8 Replacement factors firefighting (FF) sub-system

Item / Element	Replacement Frequency /Life span (years)	Estimated No of Replacements in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Structure - Fire Tanks, Fire Hose Cabinet				
Reinforcement steel	120	0	0	
RCC in all grades	120	0	0	
Water proofing treatment	10	4	4	
Half brickwork I-Class in cement mortar 1:6	60	0	0	
Plastering - walls & columns in cement mortar 1;6 (12 mm thick)	25	1	1	
Plastering -ceiling in cement mortar 1:3 (6 mm thick)	25	1	1	
Synthetic enamel paint -two coats	5	9	9	
Flooring 75 mm thick Cement concrete flooring	120	0	0	
Whitewash	2	24	24	
Firefighting & Detection Equipment				
Fire Hydrant System Internal, for Basement, External Fire Hydrant	50	0	0	Akin to Water Supply Sector
Hand Appliances, Sprinkler System for Basement,	20	2	2	
Fire Detection & Alarm System (Gas Flooding System),	20	2	2	
Supply of Fire Pumps	20	2	2	
Fixing of pumps	20	2	2	
Accessories for FF Plumbing	20	2	2	Life span taken same as fire pumps
MS Structural Works	50	0	0	

Table D-9 Replacement factors site development features sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Boundary wall works, guard room, meter room, garbage room				
PCC & lean concrete	120	0	0	
Brickwork l-Class in cement mortar 1:6 in boundary wall 230mm thick	60	0	0	
Half brick work with cement mortar 1:4 in guard room	60	0	0	
Plastering walls, columns18mm thick in cement mortar 1:6	15	3	3	
RCC in foundation /footing, columns etc	120	0	0	
Reinforcement steel in footing, columns, pillars etc	120	0	0	
MS Railing, welding and fixing of railing in boundary wall	50	0	0	
MS Structural work	50	0	0	
Concertina coil on Y-shaped angle iron frame	15	3	2	
Painting				
External paint on boundary wall and other external areas	5	9	9	
Synthetic enamel paint on MS Railing -boundary wall	5	9	9	
Synthetic enamel paint main gate and wicket gate	5	9	9	

Table D-9: Replacement factors site development features sub-system (contd…)

Item / Element	Replacement Frequency/ Life span (years)	Estimated Nos of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos))	Remarks
Security-Access control system				
Vehicle tag scanner, access control hardware & software	5	9	9	
Intercom equipment-tele handsets,	12	4	3	
UPS 1-5 KV for Control Room, Boom Barriers at Entry/Exit	15	3	2	
Cabling various sizes	12	4	3	
PVC Conduiting 20, 25 mm	50	0	0	
Approach road				
Carpeting/ resurfacing of roads	5	9	9	
Paver Blocks, 80 mm thick	50	0	0	
RCC pipes 600 mm NP3 and 250 mm NP2	75	0	0	
Internal road & pathways, Area pavement				
Brickwork in toe wall Class-I in cement mortar 1:6	60	0	0	
Granite stone-stepping stone in cement mortar 1:4	75	0	0	
Dholpur stone over 20mm thick cement mortar 1:4	75	0	0	

Table D-9: Replacement factors site development features sub-system (contd…)

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos))	Remarks
Street lighting/ Area lighting				
Light fixtures	20	2	2	
Wiring & cables	20	2	2	
Electrical accessories	20	2	2	
HDPE pipes-50 to 150 mm	50	0	0	
PVC pipes 25 to 100 mm	50	0	0	
GI wire 4 mm	25	1	1	
MS/GI electric poles	50	0	0	
Rain water harvesting system				
Rain water harvesting -UPVC Pipe 160 mm perforated	50	0	0	
Storm drainage & sub soil drainage				
R.C.C pipe 200-400 mm for Pipe culvert	75	0	0	
PCC 1:5:10 for haunches of RCC pipes and bed concrete	120	0	0	
UPVC Pipe 150 mm	50	0	0	
Cement concrete 1:5:10 - bed concrete/ haunches for UPVC pipe 150 mm	120	0	0	
Providing & fixing drain cover-in basement drain	50	0	0	
MS pipes 100 mm for sub-soil drainage with MS fittings	50	0	0	

Table D-10 Replacement factors sports facilities sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Structure Swimming Pool				
Reinforcement steel	120	0	0	
PCC& lean concrete	120	0	0	
RCC all grades	120	0	0	
Waterproofing treatment	10	4	4	
Half brickwork	60	0	0	
Full brickwork	60	0	0	
Porcelain tile	60	0	0	
Granite stone in pool edge, drain & floor 20 mm thick	75	0	0	
Protection plaster in cement mortar 1:3	15	3	3	
Epoxy-tile epoxy grout for swimming pool tiles.	60	0	0	
Swim pool drain (drain Cell type)	120	0	0	
Swim pool plumbing & water treatment, electrical works/lighting				
Recirculation pumps- various sizes	10	4	4	
Pressure filter, chemical doser, uv dis-infection unit	7	4	4	
Electrical panel suitable for 415 V, 3 phase power distribution system,	20	2	2	
Power cables various sizes	20	2	2	

Table D-10: Replacement factors sports facilities sub-system (contd…)

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years (Nos)	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Underwater Illumination, -LED lighting, Junction box	20	2	2	
UPVC pipes with fittings 63-200 mm	50	0	0	
M.S. structural work - for pipe supports, clamps, MS ladder and manhole tank covers etc.)	50	0	0	
MS pipes	50	0	0	
Badminton court - synthetic grass system -2 Nos (44ft X 20 ft)	11	4	4	
Kids playing Area - EPDM flooring	10	4	4	
Tennis court light fixtures				
Electric Pole 8 m height for Tennis Court	50	0	0	
300 W rectangular area light fixtures	20	2	2	
Gym equipment				
Treadmill	10	4	4	
Upright bike, elliptical trainer, bench press	20	2	2	
dumbbell set	50	0	0	

Table D-11 Replacement factors site beautification features sub-system

Item / Element	Replacement Frequency/ Life span (years)	Estimated No. of Replacement in 50 years	Modified No. of Replacement in 50 years (Replacement Factor) (N) (Nos)	Remarks
Arboriculture/ Soft scaping				
Supply of trees, plants, shrubs and grass	10	4	4	Assumed replacement frequency based on CPWD (2019)
Music system works at garden area	7	7	6	
Wafer bodies -filtrations, pumps, plumbing, lighting				
Water pumps various sizes	10	4	4	
Water purification -pressure sand filter, chemical doser	7	7	6	
Lighting fixtures	20	2	2	
Electrical panel 415 V	20	2	2	
Electrical cables overhead	25	1	1	

Table D-12 Cost elements for EE estimation on repair and maintenance

Sub-system	**Item**	**Reference/ Source**
Residential Towers	Repair & maintenance of apartments (civil & electrical building)	##
External water supply	Repair/maintenance of pumps	$$
	Repairs to pipeline/plumbing	$$
	Maintenance of pump house (Civil & Electrical building)	##
	Cleaning, disinfection of water tanks, pipe lines	$$
External electric supply	AMC - HT & LT Panels	$$
	AMC for circuit breakers (ACB and VCB)	$$
	Maintenance of transformer room and Diesel Generator Room (civil & electrical building)	##
	AMC-Diesel Generator Sets	$$
	Diesel Generator Sets - B, C, & D check	$$
Sewage treatment plant (STP)	AMC - STP	$$
	Maintenance of STP structure/basement (civil & electrical building)	##
Vehicle parking	Maintenance of parking (basement) (civil & electrical building)	##
Elevators	AMC elevators	$$
	Maintenance of lift lobby (civil & electrical)	##
Firefighting (FF)	AMC - FF system	$$
Site development features	AMC - Access control system, boom barrier, CCTV. hardware & software	$$
	Cleaning of storm drainage	$$
	Maintenance of street lights	$$
Sports facilities	AMC - Gym equipment	$$
	Maintenance civil & electrical-courts, swim pool building/Area, pumps	$$
Site beautification features	Arboriculture/Soft-scaping-cost of manure, replacement of soil, fertilizer	@@
	Maintenance of water bodies-pumps, lighting	$$

##- CPWD (2020), $$- Facility Management, AMC – Annual maintenance contract,
@@- CPWD (2019)

Table D-13 Cost elements for operating cost of common services

Item	Unit	Quantity	Rate (Rs/unit/month)	Amount (Rs/month)	Amount (Rs/year)	Remarks/ References
Establishment cost (manpower & office expenses)						$$
Estate manager	Nos					
Technical manager	Nos					
Security officer	Nos					
Accountant	Nos					
Housekeeping supervisor	Nos					
Accounts executive	Nos					
Plumbing engineer	Nos					
Higher management cost	Nos					
Office expenses						
Billing software	Nos					
Printing & stationary	lumpsum					
Pantry	lumpsum					
Postage	lumpsum					
Total Establishment Cost						
Cost Technical services						$$
Electrician	Nos					
Plumber	Nos					
Mason	Nos					
Carpenter	Nos					
Painter	Nos					
Helper	Nos					
Total Cost Technical Services						
Cost Security Services						$$
Security supervisor	Nos					
Male guard	Nos					
Female guard	Nos					
Mobile handset	Nos					
Total Cost Security Services						
Cost Housekeeping (staff, consumables)						$$
Housekeeping supervisor	Nos					
Housekeeping staff (male, female)	Nos					
Pantry boy	Nos					
Chemicals, expendables	lumpsum					
Total Cost Housekeeping Services						

$$- Facility management

APPENDIX E: PUBLICATIONS

The papers that have been based on the present thesis are as follows:

[A] International Conference

a) Dahiya, D. *Strategies for Skill Development for Green Building Construction*. Key note address at the International Conference on Sustainable Skill Development (SSD): Challenges and Future Perspectives, at National Institute of Technical Teachers Training & Research, Chandigarh, 18-19 February 2016, Chandigarh, India. A technical session was also chaired during the conference.

b) Dahiya, D., Laishram, B. & Guite, T. (2019). *Energy Initiatives for Empowering Smart Villages*. Paper presented at the International Conference on Smart Villages and Rural Development (COSVARD 2019) hosted by the University of Melbourne, Australia at Guwahati, India on 2-4 December 2019.

[B] Journals

a) Dahiya, D., & Laishram, B. (2023). Energy analysis of high-rise residential buildings under demolition using controlled explosion: An Indian case study. *Journal of Cleaner Production*, 426, 139190.

b) Dahiya, D., & Laishram, B. (2024). Life cycle energy analysis of buildings: A systematic review. *Building and Environment*, 252, 111160.