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# Life Cycle Energy Analysis in Buildings and Sustainability Assessment: A Literature Review

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***ABSTRACT:*** *Literature review reveals that there exist many gaps in sustainability assessment of buildings. Most of the sustainability assessment is based on life cycle energy analysis, considering embodied energy, and embodied carbon coefficients within cradle to gate system boundaries. Conditions for extension of system boundaries beyond 'cradle to gate' vary considerably from place to place and also depend on several other critical parameters such as transport, fuel efficiency, equipment efficiency, and road conditions. Literature review reveals that embodied energy and embodied carbon alone cannot accurately meet the sustainability assessment criteria. There are also numerous other assessment methodologies, suggesting solutions to the complex sustainability assessment phenomena. These methods in principle, apply appropriate sustainability development indices, evolved using critical eco parameters, extended boundary conditions and Figures of Merit. Further, it is to be noted that the more the operational energy gets streamlined, the more importance energy consumption during construction phase in a building's life cycle attains. This paper focuses in analysing available literature to identify prevailing assessment techniques, to facilitate, a consistent sustainability assessment tool.*

***Keywords:*** *Life Cycle Energy, Embodied Energy, Embodied Carbon, Sustainability Assessment, Figure of Merit, Global Warming, Construction Materials.*

## I. INTRODUCTION

Sustainable development in its absolute sense is a concept of understanding the global environment within the framework of its complex interaction between economic, social, political and environmental systems. Assessing sustainability and impact due to climate change has gained substantial importance in the present era. According to Cole [1], sustainability assessment should provide details about the environmental characteristics of a building and also to be a measure of progress towards sustainable development. Resource depletion is another phenomenon that has its immediate impact, felt in the economic, geopolitical and natural environment spheres. As cited by Klinglmair et al. [2] and mentioned in United Nation's Environmental Program, UNEP 2010 [3], depletion of natural resources including fossil fuel and metal ores pose immense threat to industrial development of developing nations. UNEP 2009 [4] records, buildings, infrastructure projects and construction industry alone contribute to 33% of anthropogenic greenhouse gas emissions leading to Global Warming and use approximately same amount of energy produced globally.

Global warming will have devastating effect resulting in sea level rise. Intergovernmental Panel for Climate Change, IPCC 2001 [5], reported that 450 mm sea-level rise can result in the potential land loss of about 10.9% and a rise of about 1 meter, can result in land mass loss of about 20.7%. 11% of the human population, as per UNDP 2007 [6], will be directly affected by the rise of 1 meter sea-level. Global warming is mainly due to built-environment and will have detrimental effect on human beings, Rockström et al. [7], Passer et al. [8], Blengini & DiCarlo, [9].

Belin [10] and Todorovic [11] affirmed that the present rate of fossil fuel consumption will entail resource exhaustion since Earth's resources are limited. They draw attention to some of the very influential building subsystems namely; i) the facades and envelopes, ii) glazing and fenestration, iii) building thermal mass and insulating materials, iv) HVAC, v) indoor air quality, which can be controlled to reduce the environmental impact due to buildings. Energy consumption during the operative and maintenance phases of building's life cycle is much higher than the initial energy consumed, but is distributed over larger span of buildings life cycle.

However, innovations in building appliances and gadgets have helped to streamline the energy consumption in the operative phase. Pöyry et al. [12] observe, the energy consumed and greenhouse gases emitted during the pre-use phase of a building are more detrimental, as compared to GHG emissions in the subsequent stages of building's life cycle period. This is due to the fact that the impact happens in a very short duration resulting in carbon spike. As the energy consumption gets controlled and streamlined in operative and maintenance phases, its relative importance in the pre use phase of building's life cycle attains considerable importance.

Reports generated by PBL, Netherlands [13], an Environmental Assessment Agency, on 'Trends in global $CO_2$ emissions'; India, USA, China and EU contribute 6.0 %, 15%, 30% and 10% respectively, totaling to 61%, to the global carbon dioxide emissions. Buildings are estimated to be responsible for two fifths of the world's material and energy flows, one sixth of its freshwater withdrawals, and one quarter of its wood harvest. In the United States, 54% of energy consumption is directly or indirectly related to building construction and operations, Kibert [14], Horvath [15].

A brief review of the research carried out in the past with respect to sustainability assessment through energy analysis is presented in this paper. The literature studied is presented in four heads namely; Alternative Materials, Life Cycle Assessment, Embodied Energy and GHG Emissions, and Importance of Construction Phase. The paper concludes with the key findings from the literature review that will help and define future research.

## II. ALTERNATIVE MATERIALS

### 2.1 Material Timeline

Materials drawn from natural resources have played significant role and as observed by **Ashby [16],** ages of mankind are identified by the dominant material that prevailed in that age. In the material timeline, stone is perceived to be the base material. Almost all anthropogenic activities have some impact on the surrounding environment and the surrounding natural environment has certain capability to absorb the impact. The current rate at which human activities are exploiting the nature and the natural resources, the threshold limit will soon be crossed resulting in catastrophic effects. Materials like stone, timber, mud etc. belonging to early material time line, hardly consumed any energy during their manufacturing processes. Quest for durable construction materials lead to the invention of burnt bricks, where firewood was used as primary fuel source. Use of metals followed by lime based products as durable construction materials, was the next phase of development where external energy sources were used. Invention of Cement and steel followed by plastics revolutionized the role of construction materials in the modern era.

### 2.2 Modern Building Materials

Modern day building materials like steel, cement, ceramics, polymers, plastics, aluminium are high energy intensive. Hence, energy consumption, consumption of raw materials, transportation of materials and finished products gain importance in understanding the meaning of long term sustainability. These activities, hence call for incorporation of alternative building materials and technologies for minimum environmental impact, while arriving at sustainable building solutions. Considering three different building typologies, Venkatarama Reddy [17], illustrated reduction of 50% of embodied energy consumption using low energy alternative building materials. Results showed that RCC framed structures with burnt clay brick infill walls, consumed highest embodied energy in the order of 4.21 GJ/sqm as compared to conventional load bearing brick wall structure with about 2.92 GJ/sqm. Load bearing wall structures with Stabilized Mud Blocks consumed about 1.61 GJ/sqm. This is found to be consistent with the study made by Shams et al. [18], who concluded that by using alternative building materials and technologies, energy consumption can be reduced by about 30% to 52%.

In Indian scenario, organisations like Center for Sustainable Technologies (CST), Building Materials and Technology Promotion Council (BMTPC), Indian Institute of Science (IISc), are working towards a comprehensive and integrated approach for promoting cost-effective, eco-friendly, energy-efficient alternative building materials. For example, Stabilized Mud Blocks (SMBs), with wet crushing strength of 3 to 4 MPa and 7% of cement as stabilizer, can save 70% energy as compared to clay bricks and are 20-40% economical. Thus, interpretation of sustainability levels in buildings and other infrastructure projects in the initial stages, help in replacing energy intensive materials with low energy materials to reduce global warming.

It was noted by Asif et al. [19], that materials used in construction of a frame consume about 50% of the total energy consumed by a building and by using alternative building materials with low embodied energy such as hollow concrete blocks, soil cement blocks, fly ash bricks etc. in place of energy intensive building materials such as reinforced concrete, saving in the order of about 20% can be achieved. They illustrated that concrete and ceramic to be two major energy intensive materials in building construction that are found to contribute significantly to $CO_2$ emission. These views are in consistent with studies carried out by Huberman and Pearlmutter [20], Chen et al. [21]. Substantiating these observations, Thormark [22, 23], Blengini [24] noted reduced energy consumption by using recycled materials. For instance, usage of recycled steel and aluminium entails more than 50% of energy savings.

### 2.3 Case Studies

Building materials manufacturing process is found to be high energy intensive and contributes significantly to greenhouse gas (GHG) emissions. Impact of building materials and their manufacturing processes on natural environment have been studied at length by Buchanan and Honey [25], Suzuki et al. [26], Oka et al. [27], Debnath et al. [28]. These studies pertain to New Zealand, Japan and India respectively. Thormark [22], established formula for computing Recycling Potential of a material keeping two scenarios namely 'maximum recycle potential' and 'maximum reuse potential'.

Reddy and Jagadish [29], while suggesting alternative materials enabling reduction in energy consumption, observed that, masonry as a subsystem in a building constitutes a major component. In Indian context, they carried out study on five building typologies and compared energy consumption in each case. Energy consumption by different types of blocks is tabulated in **Table 2.1**. They also observed, Cement to be one of the most consumed construction material with an average energy consumption of 5.85 MJ/kg.

**Table 2.1:** Energy Consumption in Walling Blocks

| Block type | Energy Consumption (MJ) | Size (mm) |
|---|---|---|
| Burnt Clay Bricks (TMBs) | 4.25 | 230 x 110 x 75 |
| Hollow Concrete Blocks (HCBs) | 12.5 to 15 | 400 x 200 x 200 |
| Stabilized Mud Blocks (SMBs) | 2.75 to 3.75 | 230 x 190 x 100 |
| Steam Cured Mud Blocks ( SCMBs) | 6.7 | 230 x 190 x 100 |

Dimoudi and Tompa [30], demonstrated that concrete and steel contribute 62% and 11%, Brick envelope about 8%, plastering about 7% and aluminium composite panel about 4% to GHG emission. Buchanan and Honey [25], used energy coefficients as reported by Baird and Chan [31], to determine total embodied carbon in buildings. They recommended shift from steel, concrete and aluminium to greater use of wood in construction which would considerably contributes in reducing carbon dioxide emissions.

Sagheb et al. [32], found from their study that by replacing convention materials in a building construction by alternative materials with low embodied energy, GHG impact can be reduced by about 35%. This is consistent with the observations made by Thormark [23] and Blengini [24]. Importance of using low energy alternative materials was also admitted by Gonzalea and Navarro [33]. Based on case study taken up by them, they concluded that 30% reduction in carbon dioxide emission is possible by adopting low energy construction materials.

Environmental impact in China based on material flow analysis, taking materials consumed by construction industry till now and projected up to 2050, was assessed by Huang et al. [34]. Results showed that in the coming years, natural material extraction and GHG impact in China will start declining. However, they laid emphasis on recyclability and reuse of materials to maintain sustainable growth. Reddy and Jagadish [29], recorded, among various subsystems constituting a building system, brick masonry consumes high amount of energy in the order of 2141 MJ/cum. In comparison, SMBs consume 715 MJ/cum. Hollow concrete block masonry requires about 38–45% of the brick masonry energy. SMB masonry is found to be the most energy efficient alternative material. In case of Vault roofs with SMBs, as alternative low energy roofing system, it is observed that energy consumption is in the order of 418 MJ / sqm while for vault with burnt brick it is about 575 MJ / sqm.

Sabnis and Pranesh [35], studied energy impact of commonly used three formwork systems in India and expressed their derivations in terms of interaction values, evaluated using Figure of merit as a tool. They evolved three different interaction equations $I_1$, $I_2$ and $I_3$ as interaction between Materials and Embodied Energy; Embodied Energy and GHG; GHG and Materials respectively. Overall interaction value was taken as algebraic sum of three interaction values. It was observed that conventional formwork with steel floor plates exhibited total interaction value of 90254 per square meter of construction area as against values of 31781 and 30490 for formwork systems with plywood and aluminium floor plates. Thus by choosing aluminium formwork in place of conventional formwork, total energy impact can be reduced by about 33%.

## III. LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is one of the most accepted and widely used tools to evaluate and quantify the material and energy flows in a building. The system boundaries normally drawn in LCA are cradle to cradle. As stipulated in ISO 14040 [36], LCA comprises of four stages namely; Goal and Scope definition, Life Cycle Inventory (LCI), Impact assessment and, Interpretation. **Fig 1** shows stages of LCA as stipulated in ISO 14040, 2006 [36].

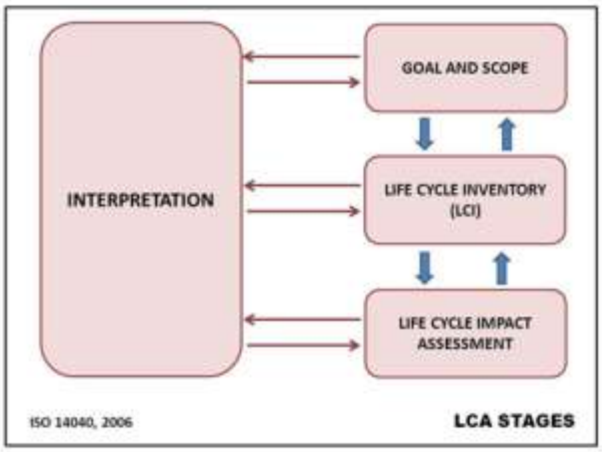


**Fig 1**. LCA Stages as per ISO 14040, 2006

In the above four stages, second stage involves in quantification of material and energy inputs, third stage involves impact assessment due to these inputs. Impact assessment is then interpreted in terms of energy consumption and GHG emissions in aggregation. There are two commonly accepted LCA methods, Process method and Input-output method. Both these methods have their own limitations due to lack of reliable data available and various processes involved, as observed by Treloar et al. [37], Thormark [23], and Junnila et al. [38]. Hence, combination of both these methods, namely, Hybrid energy analysis is adopted. Hybrid energy analysis increases the overall reliability and the environmental impact, Treloar [39]. This is in consistency with studies made by Crawford [40]. Further, use of hybrid LCA method is also recommended to be more appropriate for construction industry as observed by Bilec et al. [41], Guggemos & Horvath, [42] and Suh et al. [43]. Zhang and Wang [44], with their case study on buildings located in china, evaluated carbon emission using both methods of LCA namely process method and Input-Output method. Both results revealed that material manufacturing was the main contributor to GHG emissions accounting to 80-90 % of the total emission. They also observed that when subsystems of a building system are taken in to account, main frame including foundation contributes the most. This is in line with the observations made by Gholamreza et al. [45]. Hong et al. [46], carried out detailed energy impact assessment of buildings using hybrid LCA approach during construction phase by defining construction process boundaries and by dividing the entire process into three main module namely, material manufacturing, transportation and construction. These three modules respectively consumed 94.89, 1.08 and 4.03 % of total energy. Obtained results also showed global warming potential values to be in the order of 95.16, 1.76 and 3.08 % respectively. Ristimaki et al. [47], suggested defining the life time period as 100 years while assessing the total energy impact of a building using LCA through cradle to grave boundary condition.

## IV. EMBODIED ENERGY AND GHG EMISSIONS

Embodied energy and greenhouse gas emission are the two critical indicators in the impact assessment of environment. While embodied energy is expended in the initial stages of building construction, operational energy accrues over the life span of a building and is distributive in nature. In general, studies have established that higher embodied energy entails higher greenhouse gas emissions and higher global warming. Hence, embodied energy plays vital role in sustainability assessment of a building or any other infrastructure project. Treloar et al. [48] state, Embodied energy (EE) is the energy required to produce a product through all its processes from raw material extraction to finished product stage. This is consistent with the definition given by Bousted and Hancock as cited by Langston and Langston [49]. According to them, total Embodied energy includes not only all the upstream processes for materials but also the energy spent for transportation. According to Alcorn and Baird [50], embodied energy encompasses all the energy consumed from extraction stage, manufacturing stage to implementation stage along with the energy consumed in transportation and demolition.

In the context of life cycle energy analysis as applied to sustainability assessment, role of embodied energy is to be understood with clarity and there are several ways in which researchers have approached embodied energy while analyzing the energy consumption. Miller [51], observes, the term embodied energy has varied definitions with different boundary conditions. Embodied energy is also split into three categories namely, energy consumed in the production of basic building materials, energy needed for transportation of the building materials, and lastly, energy required for assembling the various materials to form the building.

United Nation's Intergovernmental Panel on climate change, IPCC 2001 [5], recognizes greenhouse gas emissions to be the primary contributors to global warming. Composition of greenhouse gasses is found to be in the order of 76% Carbon dioxide, 13% Methane, 6% Nitrogen oxides and 5% Fluorocarbons. Carbon dioxide thus, is found to contribute significantly to global warming, Sagheb et al. [32]. The total life cycle energy required in the construction of a building includes two types of energies namely, the direct energy used in the actual construction and assembly process, the indirect energy, that is required to manufacture the materials and other constituents of a building, as per Crowther [52].

Ding [53], Fay et al. [54], Treloar [39], identified different types of embodied energy expended during different stages of building's life cycle as; direct energy, indirect energy, initial energy, recurrent energy, demolition energy and operating energy. Cole and Kernan [55], defined operational energy to be the energy required for heating, cooling, ventilation, lighting and running other appliances in the building. They also illustrated that it varies with the building typology, utility, function, number of hours it is occupied, number of users, climate, efficiency of the building equipment etc. Hence it was suggested to divide the energy consumption based on the usage, to have correctness in assessment.

As cited by Dixit et al. [56] and observed by Crawford and Treloar [57], Buchanan and Honey [25], Pullen [58], technological advancements will enhance material properties and innovations bring in improvements in manufacturing processes affecting embodied energy values. Hammond and Jones [59], while establishing the inventory of carbon and energy, considered data from modern resources and energy coefficients proposed in their inventory are more relevant in the present times. Baird et al. [60] adopted hybrid analysis method while computing and updating embodied energy coefficients database of New Zealand building materials.

### 4.1 Life Cycle Energy Analysis - Case Studies

Bansal et al. [61], based on a case study comprising of 122 residential buildings with different building materials and different building typologies applicable for Indian conditions, concluded that embodied energy values vary between 2092 MJ/sqm to 4257 MJ/sqm with varying usage of construction materials. The study also indicated that use of low embodied energy materials does not necessarily mean low cost of construction. The assessment methodology adopted has some limitations. These limitations are due to non-consideration of;

- Transport energy,
- Design life of materials and
- Impact of individual components like foundations, plastering, roofing, formwork etc.

Due to vide variations in embodied energy values which are mainly process and efficiency dependent, it is difficult to predict a single embodied energy value. Hence it is suggested to represent embodied energy as range of values. This is in consistent with the study carried out by Praseeda et al. [62]. Hong et al. [46], evaluated energy consumption and GHG emission under three critical phases namely- Material manufacturing, Transportation and Construction. Results obtained for EE and GHG emissions per sqm are tabulated in **Table 2.2**

**Table 2.2:** Stage wise energy and greenhouse gas evaluation per sqm

| Stages | Energy Consumption (MJ) | GHG Emission ($kgCO_2e$) |
|---|---|---|
| Material manufacturing | 2641 | 258 |
| Transportation | 30 | 5 |
| Construction | 112 | 8 |
| Total | 2783 | 271 |

As per the observations made by Thormark [23], total energy consumption in a buildings life cycle is in the order of 7033 MJ / sqm of floor area for construction phase including transport energy after demolition of building. Operational energy for 50 years design life was in the order of 8200 MJ/sqm of floor area. In respect of low energy buildings, Thormark observed the energy consumption to be in the order of about 252 MJ/sqm in consistent with the values shown by Feist [63].

Buchanan et al. [25], with reference to buildings in New Zealand, investigated the impact of GHG emission due to building construction using New Zealand energy coefficients. He demonstrated that long term reduction in $CO_2$ emissions is possible only by adopting to renewable energy resources, reducing fossil fuel combustion and effective implementation of techniques that reduce per capita energy consumption during the operative phase of buildings. Results found that the energy consumption for the case study taken up, to be in the order of 5.36, 3.95, 2.66 GJ/sqm for high energy, moderate energy and low energy buildings respectively. According to them, moderate energy buildings are the most commonly constructed buildings. In case of industrial building with steel structure, total energy consumption to be in the order of 3.2 GJ/sqm. Energy coefficient used for transporting materials for a distance of 100 km was 230 MJ per 1000 kg or 0.00230 MJ/kg/km. This is consistent with the value taken as 0.00280 MJ / kg / km by Sabnis and Pranesh [64].

Debnath et al. [28] attempted computing total energy consumption in three building typologies namely, single, double and multistoried in India. It was observed that steel, concrete and bricks contribute maximum energy consumption and for a sustainable solution, alternatives for these materials to be found. Average energy consumption was found to be in the order of 3-5 GJ / sqm of built-up area. They also made an interesting observation that as the floor area increases from 50 to 200 sqm, energy consumption per unit area decreases, from 5 to 4.1 GJ in single story buildings, 4.2 to 3.7 in two story buildings and 4.3 to 3.1 GJ in four story buildings. It was also observed that cement, steel and bricks contributed to maximum energy consumption in the overall consumption in all three building typologies.

Suzuki et al. [26] computed total energy consumption per sqm of built up area applicable to conditions more suitable to Japan. It was found that energy consumed by RC framed buildings to be in the order of about 8-10 GJ/sqm. Study carried out by Suzuki et al. also found that for buildings constructed with timber, energy consumption is about 3 GJ/sqm.

According to Treloar et al. [48] high rise buildings require more energy intensive materials to meet the structural requirements as compared to low rise buildings. They also observed that the embodied energy is 20 to 50 times the annual operational energy in the context of Australian buildings. Aye et al. [65] used embodied energy and embodied carbon coefficients from Building Performance Research of New Zealand. Coefficients are based on process based hybrid analysis. Their case study analysis considered only some major building elements such as foundations, RCC and facades. Analysis showed that concrete framed structure consumed 6714 MJ / sqm of floor area while steel buildings consumed 11415 MJ / sqm. Thus, steel buildings consume 70% more energy than concrete framed buildings. Similarly, in case of embodied carbon, GHG emission for concrete building was found to be 470 kg $CO_2e$ /sqm while for steel framed buildings it was in the order of 780 kg $CO_2e$ / sqm.

Sartori and Hestnes [66], studied life cycle energy consumption in case of three building typologies namely, conventional, low energy and zero energy. Their results showed, life cycle energy of zero energy buildings is higher than the low energy buildings. In the same context, Winther and Hestnes [67], concluded that strategically designed low energy buildings are more effective than zero energy buildings from life cycle energy perspective. Amalia Pöyry et al. [68] estimated GHG emission in respect of a low energy building located in Finland. GHG emission was found to be in the order of 470 kg $CO_2e$. They also found that RCC frame contributes significantly to GHG emission in the order of about 40%. Earlier studies made by Passer et al. [8], reported total GHG emission due to building construction to be in the order of 500-800 kg $CO_2e$.

Blengini & DiCarlo [9], based on the study carried out on two buildings reported overall GHG emission due to construction in the order of 600 – 800 kg $CO_2$e.

Dimoudi and Tompa [30], based on their study carried out on two office buildings in Athens, Greece, observed embodied energy consumption to be in the order of 1.93 and 3.27 GJ/sqm and, embodied carbon to be in the order of 200 and 289 kg $CO_2$ e. In case of paints, it was found that embodied energy is less than 1% and thus painting has negligible impact.

Gholamreza et al. [45] carried out studies on 14 buildings in Iran to assess the energy consumption during production and construction phases of building's life cycle. They demonstrated following results, **Table 2.3**

**Table 2.3:** Energy Consumption through different phases of building's life cycle per sqm

| Phase | Energy consumption (MJ/sqm) | |
|---|---|---|
| | **Low** | **High** |
| Production of Materials | 2110 | 3610 |
| Transportation | 140 | 200 |
| Actual construction | 120 | 170 |
| Overall energy consumption | 2360 | 4160 |

Gustavsson and Joelsson [69], showed that the primary energy for the production of conventional and low-energy residential buildings can vary from 45% to 60% of the total energy consumption. With study carried out on two buildings in Shanghai, china, Xing et al. [70] demonstrated that energy consumption in buildings with concrete frames is lower than buildings with steel structures. This is in consistency with the studies made by Foraboschi et al. [71].

Recent researches and scientific advancements have considerably assisted in streamlining the energy consumption in operational phase of building's life cycle. However, accurate assessment of energy impact is still not possible due to lack of reliable data and lack of acceptable methodologies, Sartori and Hestnes [66], Geordano et al. [72], ISO 2016 [73], European Norms [74]. Gonzalez and Navarro [33], established relationship between high embodied energy and carbon dioxide emission by comparing energy values based on their case studies. They asserted that high embodied energy material entails higher $CO_2$ emissions as compared to low embodied energy materials.

Luo et al. [75], assessed carbon dioxide emissions in 78 office buildings of China to evolve a prediction model for pre-use phase of buildings. Buildings chosen were all RCC framed buildings varying in heights; 19 buildings below 24 meters, 44 high-rise buildings between 24-100 meters and 15 super tall buildings above 100 meters. Their study revealed, total weighted average of carbon dioxide emission to be in the order of 316.44 kg$CO_2$ / sqm and $CO_2$ emissions in respect of civil engineering activities alone contributing to about 76% of the total emissions. They also concluded that, $CO_2$ emission impact is 1.5 times higher in super tall buildings as compared to multi story buildings.

Ignacio et al. [76], observe in their investigation that each building results in an average energy consumption of 5754 MJ/sqm and $CO_2$ emission due to steel, cement and ceramics aggregating to nearly 69% of the total emissions. According to studies carried out by Koroneos et al. [77], Bovea et al. [78], Nicoletti et al. [79], energy consumption due to ceramics is of high intensity due to firing of ceramics at high temperatures. Tatsua et al. [80], with their study carried out on commercial buildings in Japan, found that construction cost per sqm is proportional to the energy consumption per sqm. The total energy consumption of office buildings was to be in the order of 8 to 10 GJ / sqm.

Yohanis and Norton [81], based on impact assessment study on a single story building in UK, established a relation between envelope of a building and the life cycle energy. They found that glazing as an envelope, affects the impact intensity of embodied and operational energies. When glazing area is more than 55% of the total envelope area, embodied energy is found to be low while operational energy is higher.

Yan et al. [82], based on their review, illustrated that building materials, transportation, construction equipment, energy consumed during manufacturing processes of materials and construction waste, contribute maximum to GHG emissions during the construction stage. They concluded from their findings that GHG emissions due to material manufacturing and fuel consumed by construction equipment accounted for about 92%. This is in consistent with the observations made by Cass and Mukherjee [83].

Treloar et al. [48], evaluated five tall buildings ranging in height from a few story to 52 story office buildings with embodied energy perspective. Each building was divided into 13 important building activity categories and energy coefficients applied to determine the energy consumption. They established a relation between height of the building and energy consumption. Their investigation showed that taller buildings are high energy intensive and consume approximately 60% higher energy as compared to low-rise buildings. Their findings are found to be consistent with Aye et al. [65].

Shukla et al. [84], studied life cycle energy of an adobe house by aggregating energy consumption by each component of a building. Specifications stipulated for the case study building comprised, vault roof made of adobe with mud mortar, Walls with stabilised soil cement blocks, mud plaster, white wash for interior walls and foundation with plain cement concrete made using brick bats as coarse aggregate. Results showed significant reduction in energy consumption level as compared to conventional RCC building. Total embodied energy for Adobe House was found to be in the order of 4750 MJ/sqm of built up area.

Total life cycle energy consumption in a Swedish residential building including operation phase consumption and recycling potential of building materials was assessed by Thormark [85]. Energy for operation was taken at 50 kWh/sqm or 180 MJ/sqm per year average. Results indicated that up to 25% reduction in energy consumption can be achieved by using recycled materials. The study concluded that, while designing new buildings it is important to pay attention not only to low energy materials but also to the aspect of recycling and reuse.

### 4.2 Truncation Errors

Impact assessment using life cycle analysis has its own limitations due to non-inclusion of certain upstream activities within system boundaries. As a result of this, the assessment suffers from Truncation error as high as 50%, as mentioned by Lenzen and Treloar [86]. Lenzen [87], observes possibility of truncation errors to the extent of 50% in using conventional process analysis. This is in consistency with the another study made by Treloar et al. [88], wherein, the process analysis errors vary to the extent of 20% and recommends hybrid analysis for assessing embodied energy impact. Pullen [89] notes, these inconsistencies are due to non-inclusion of upstream and downstream process in the conventional process analysis.

### 4.3 Embodied Energy vs Operative Energy

Establishing relation between operating energy and embodied energy plays critical role in understanding the life cycle energy of a building. Thormark [90] observed, operational energy during the assumed service life of 50 years is as high as 85% compared to energy consumed during other phases in a life cycle of a building. While Commonwealth Scientific and Industrial Research Organisation-CSIRO, Australia [91], have established that, embodied energy of an average residential building in Australia is equivalent to fifteen years of operational energy. Crawford and Treloar [57], based on their study suggest, embodied energy of a residential unit in Australia is 20-50 times the annual operational energy.

### 4.4 Coefficients and Range values

As cited by Wolf et al. [92], Royal Institute of Chartered Surveyors, RICS 2012 [93] published a methodology using embodied carbon coefficients sourced from ICE database, for computing $CO_2$ equivalent for buildings and materials. This methodology was applied to 53 case study buildings. It was observed that GHG emission was in the range of 395 to 3250 $kgCO_2e$ per sqm.

Ramesh et al. [94] carried out studies on 73 buildings across 13 countries to assess the impact of life cycle energy in various types of buildings. The data collected was predominantly for cold countries. Results showed, life cycle energy of conventional buildings fell in the range of 540-1440 MJ/sqm (150-400 kWh/sqm) as against 900-1920 MJ/sqm (250-550 kWh/sqm) for office buildings.

Due to varying upstream extraction and manufacturing processes, mode of transport and associated distances, accurate assessment of energy consumption and its impact is difficult to determine. Hence, many researchers have recommended using range values for energy coefficients. Dixit et al. [56], observed wide variations in embodied energy values mainly due to inconsistencies in the data used and applied for a particular geographic location. This finding converges with the observation made by Wolf et al. [92], in respect of published energy values primarily due to data inconsistencies that are geographically not coherent.

Clark [95], 2013, based on case studies of office buildings obtained wide range of embodied carbon values, 300-1650 $kgCO_2e$ / sqm. Ding [96], observed through review of previous literature, ascertained wide variation existed in the embodied energy in the range of 3600-19000 MJ / sqm. Eton and Amato [97], studied four categories of office buildings constructed using steel, concrete, composite and precast technologies to note GHG emissions to vary from 600 to 850 $kgCO_2e$ / sqm

Sabnis and Pranesh [35, 98], have based their sustainability assessment of buildings on the ICE database developed by Hammond and Jones [99]. Results are found to be in consistent with already published values by several other researchers. Embodied Energy values of building materials along with GHG emissions are sourced from Inventory of Carbon and Energy (ICE), open source database, version 2, due to their large degree of acceptance. ICE inventory database has its system boundaries from cradle to gate including all activities from material extraction to product ready to deliver to site for implementation. Hammond and Jones [99] opine that energy consumption involved in transportation to site and erection processes marginally modify the data.

## V. IMPORTANCE OF CONSTRUCTION PHASE

Energy consumption and GHG emissions that occur during construction phase peak in a short period and are more detrimental in comparison to the emissions that occur during the operational phase. In operative and maintenance phase the impact is distributed throughout the design life of a building and more or less controlled. Thus, the relative importance of energy consumption and GHG emissions in the pre use phase of building's life cycle attains higher importance, Pöyry et al. [68]. In another case study on low energy building in Finland, they reported, the spike theory to hold good even for low energy buildings.

According to Crookes and Wit [100], environmental assessment should be carried out in the initial stages to minimize consumption of natural resources and detrimental effect of building materials on natural environment. This is in agreement with the studies carried out by Lawton [101]. Lawton emphasizes the need for sustainability assessment at early stages so that many options can be exercised to minimize the detrimental effect of built environment and depletion of natural resources. Independent studies carried out by Blengini and Carlo [9], Saynajoki et al. [102], Manish et al. [103], advocate higher emphasis in quantifying the energy impact during pre-construction and actual construction phases.

Sayanajoki et al. [102], identified through their study agreed with appearance of carbon spike during the new construction inevitable and hence to be mitigated by using appropriate low energy building materials. The spike is also due to varying time periods considered in life cycle analysis. They illustrated that climate change goals can be achieved by reducing carbon emission during construction phase.

Takano et al. [104] based on their study on three categories of buildings drew relationship between material selection and life cycle energy impacts. Three categories they considered were Structural frame, envelope and other components constituting a building. It was found that among the three, material selection for structural-frame category attains importance due to its high energy consumption. It is generally seen from several studies carried out that, computation of operational energy through operative phase of a building's life cycle is less complicated than determining embodied energy during construction phase of building's life cycle. Computation of embodied energy includes all processes from raw material extraction to final demolition and disposal, Langston and Langston [49]. Further, due to non-availability of consistent data and accurate methodology in computing embodied energy, there are bound to be wide variations in measured values of embodied energy, as observed by Crowther [52] and Miller [51].

Horvath [15], noted that assessing of environmental impact due to construction is complex as several parameters are included and reliable data not available. For overall assessment, impact due to other phases of building's life cycle, other than use phase, to be included. Further, energy saving due to reuse and recycling of materials is also to be highlighted. As a corollary to this, Hoseini et al. [105], suggested to achieve sustainability by considering respective features of a building during conceptual stages.

Post 1990, there are extensive studies in respect of life cycle energy and life cycle GHG emissions suggesting mitigation strategies during the use phase of buildings including studies carried out by Sartori and Hestnes [66], Sharma et al. [106], Khasreen et al. [107]. Since Energy and GHG emissions are high during building construction which happens within a short period, impact due to construction materials are to be considered in the overall interpretation of the impact assessment, as noted by Blengini and Carlo [9], Saynajoki [102], Karimpour [108].

## VI. DISCUSSIONS

Construction activities and processes continue to be the largest consumers of materials and energy. They also are the significant polluters of on global scale. As of now, a framework for evaluating embodied energy impact is substantially developed but not devoid of some limitations and inaccuracies due to complexities involved in assessing the energy consumed during various processes. The current evaluation is based on standard methods of process Analysis, input-Output Analysis and Hybrid Analysis. In most cases, Life Cycle Analysis assumes system boundaries as 'Cradle to Gate' and arrives at total impact based on EE coefficients developed in developed countries. Further, reduction in impact of construction materials is suggested based on comparison between total EE of materials used in construction vs. reduced EE of alternate construction materials with low EE.

There are several studies assessing energy consumption during maintenance and operating phases of building's life cycle. Energy consumption during these phases is found to be higher than the energy consumed during preconstruction phase but distributed over a larger life span of a building. Due to severe complexities involved in arriving at accurate EE coefficients, a standard platform encapsulating construction methodologies, transportation, recyclability and reusability of materials is required to be evolved.

From the literature review carried out, it is assimilated that extensive published data is available in respect of energy consumption by convention buildings, low energy buildings taking into consideration several vital eco-indicators. In general, following attributes have been suggested by various investigators;

- Resource depletion has enormous impact on economic and geopolitical spheres.
- Rise in sea level due to global warming will result in land mass loss by 21%.
- Energy consumption is higher during operative phase of building's life cycle but distributed over a larger span of building's design life.
- Carbon spike phenomenon observed during the initial construction phase and hence has higher detrimental effect. Therefore, analyzing energy consumption during the pre-use phase attains higher importance.
- By using low energy alternative materials and construction methodologies, it is possible to reduce the impact due to energy consumption and GHG emissions, by about 30-40%
- Recyclability and Reuse of materials are also two critical parameters contributing in carbon mitigation.
- There is need to develop new sustainability indices applicable to locations with different climatic, social, cultural, political economic conditions. Such new tools should have their boundaries set from cradle to cradle.
- New tools to assist sustainability assessment during the initial stages of a project, say during design or concept stage, so as to evolve strategies for using effective alternative materials, appropriate construction strategies during actual construction phase.
- Figure of Merit with different types of parameters has been used in many cases for constructing and developing quantitative expressions in overall sustainability assessment.
- Impact assessment using life cycle analysis has its own limitations due to non-inclusion of certain upstream activities within system boundaries. As a result of this, the assessment suffers from Truncation error as high as 50%.
- Sabnis and Pranesh [109], suggested a non dimensional hybrid tool using Figure of Merit for assessing sustainability levels in buildings.

## VII. CONCLUSION

Current literature review reveals that there exist many gaps in sustainability assessment and those have to be addressed. Majority assessment is based on energy analysis in the framework of embodied energy and embodied carbon. There are several researches approaching the complex sustainability assessment phenomena by applying suitable sustainability development indices evolved by considering critical eco parameters and Figures of Merit. Embodied energy and embodied carbon alone cannot accurately assess the sustainability level of a building. They have to be integrated with other indicators.

Further, there are several published papers emphasizing the importance of impact assessment during the construction phase of a building or any other infrastructure project. The more the operational energy gets streamlined, the more importance construction phase in a building's life cycle attains. Literature review also calls for establishing benchmarking projects with overall low energy capabilities for comparison and sustainability levels.

The literature review has considerably helped to deliberate on the gaps existing in available literature and suitable methods developed in assessing the sustainability levels that can be applied to individual buildings, building clusters. One of the biggest gaps that is observed is that none of the methods encompass material properties while analyzing the impact due to Built Environment.

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