# Protocol for Embodied Energy Measurement Parameters

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## Abstract

The building construction industry consumes large amount of resources and energy and owing to current global population and affluence increase trends, a trend projected to aggravate in the near future. Buildings consume approximately 37 percent of total global energy; during the construction phase in the form of embodied energy and during the operation phase as operating energy. Recent studies have considered the significance of embodied energy inherent in building materials and have proven that improved technology could reduce operating energy but embodied energy could only be reduced if low energy intensive materials are preferred and used in buildings. Existing embodied energy templates, parameters and inventories differ in the measurement standards and are inconsistent, fragmented and often incompatible. Therefore there is no reliable protocol regarding embodied energy measurement parameters that could contribute to energy conservation practices, environmental decision-making, eco-labeling and low embodied energy material preference. Embodied energy measurement is a part of Life Cycle Assessment (LCA). Current standards and codes of practice for LCA could provide direction to the process of embodied energy calculation. International Standardization Organization (ISO) and the Society for Environmental Toxicology and Chemistry (SETAC) are among noteworthy institutions that are responsible of standardization and scientific development of LCA respectively. However recent research has pointed out shortcomings in international standards for LCA thereby indicating the need for protocol improvement. This paper focuses on identifying parameters that are causing variation and inconsistencies in embodied energy results and on pointing out issues that need to be addressed.

**Keywords:** building materials, embodied energy, life cycle assessment, energy consumption in construction industry, embodied energy protocol.

# 1. Introduction

The construction industry consumes two-fifths of the globe's raw stone, gravel, and sand and one-fourth of virgin wood. It consumes 40 percent of total energy and 16 percent of water annually (Ding, 2004; Horvath, 2004; Urge- Vorsatz and Novikova, 2006; Langston and Langston, 2008; Lippiatt, 1999). An anticipated radical shift in global population from 6.5 billion in 2005 to approximately 9 billion in 2035 (Fernández-Solís, 2008) indicates the graveness of the situation of material and energy consumption as a result of an eventual increase in construction activities. The total energy consumed by the building throughout its life cycle includes embodied energy (EE) and operating energy (OE). Embodied energy (EE) is embedded in building materials during all processes of production, on site construction and final demolition and disposal while, operating energy (OE) is consumed in operating and maintaining the inside environment (Crowther, 1999; Ding, 2004).

Until recently, the share of operating energy was considered larger in the total life cycle energy of a building. However, due to advent of energy efficient equipments and high performance envelope materials, the potential for curbing operating energy has increased and current emphasis of energy conservation has shifted towards embodied energy in building materials (Keoleian et al., 2001; Ding, 2004; Hannon et al., 1978; Nassen et al., 2007; Crowther, 1999; Sartori and Hestnes, 2007). According to Ding (2004), the production of building components offsite accounts for 75 percent of the total energy sequestered in a building (Spence and Mulligan, 1995). This percentage of energy is gradually increasing due to the use of high-energy intensive materials (Sartori and Hestnes, 2007; Langston and Langston, 2008).

Langston and Langston (2008) suggest that the calculation of embodied energy is more complex and time consuming than determining operating energy. Furthermore, there exists no apt method that could calculate embodied energy accurately and consistently (Miller, 2001; Crowther, 1999). Moreover, the process of embodied energy analysis lacks standardization and requires more clarification and guidelines (Pullen, 1996; Pears, 1996; Menzies et al., 2007). Standards like ISO 14040 and 14044 and SETAC (Code of Practice) present requirements and guidelines for the process of Life Cycle Assessment (LCA) of materials or products (Udo de Haes and Heijungs, 2007; Fava, 2005; Rebitzer et al., 2004; Ross et al., 2002: Zamagni et al., 2008; Horne et al., 2009: Dooley, 2001; SETAC, 2008; Levan, 1995). EE analysis is a subpart of LCA that appears in life cycle energy analysis stage (Lawson, 1996; Atkinson et al., 1996). LCA guidelines could be used to provide direction to EE analysis, but parameters like feedstock energy and primary and delivered energy need elaboration. Furthermore, issues such as, system boundary selection and embodied energy calculation methodology are not addressed by these standards. Various factors such as temporal, technological, and geographic representation of the energy data cause wide variation in the embodied energy data (Crowther, 1999; Ding, 2004; Langston and Langston, 2008; Miller, 2001; Lenzen, 2001).

This paper is focused upon identifying differing parameters that cause variation and inconsistency in embodied energy results and identifies the need to develop a protocol to standardize the embodied energy calculation process.

# 2. Research method

The research method adopted is similar to Literature Based Discovery (LBD), widely used in the realm of biomedical science, which was proposed by Dr. Don R. Swanson from the University of Chicago. In 1986, Swanson adopted the LBD research method in biomedical science studies, and was successful in creating new knowledge (Weeber et al., 2001). The concept of LBD demonstrates great potential that has been widely acknowledged by research communities (Weeber et al., 2001; Weeber, 2007; Kostoff et al., 2008). Kenneth A. Cory from Wayne State University, Detroit, has demonstrated that this research method of creating new knowledge is valid outside of the biomedical science field (Weeber et al., 2001; Weeber, 2007). This paper applies a similar approach by referring to various literature sources such as, journal papers, conference papers, dissertations and scientific and technical reports, in order to identify parameters that are causing variations in the embodied energy database and to point out issues that need to be addressed for standardization of embodied energy calculation. The information is presented in the form of a matrix after identifying the parameters and issues. Furthermore, respective sources are mentioned in the matrix, which are referenced to extract the required information.

# 3. Literature review

## 3.1. Interpretation of embodied energy: difference of opinion

Buildings are constructed with a variety of building materials that consumes energy throughout their stages of manufacture, use and deconstruction. These stages consist of raw material extraction, transport, manufacture, assembly, installation as well as its disassembly, deconstruction and decomposition. Miller (2001) reveals that, the term “embodied energy” has been interpreted in a variety of ways, and its published measurements are quite unclear. Crowther (1999) defines embodied energy as “the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings”. Treloar et al. (2001b) explain, “embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes, upstream (i.e. traceable backwards from the finished product to consideration of raw materials).” Likewise, a more comprehensive definition, provided by Baird, 1994; Edwards and Stewart, 1994; Howard and Roberts, 1995; Lawson, 1996; Cole and Kernan, 1996 (As cited in Ding, 2004), proposes that “embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building.” These definitions represent the difference of opinion about the system boundaries to be included in embodied energy analysis.

## 3.2. Embodied energy modeling

Buildings consume a total energy that is compose of (Ding, 2004; Fay and Treloar, 1998; Treloar, 1998):

**Direct Energy**: Energy consumed in various onsite and offsite operations like construction, prefabrication, transportation and administration. This includes energy inputs in construction and assembly on site, prefabrication of building components offsite and transportation involved in various onsite and offsite processes.

**Indirect Energy**: Energy consumed in manufacturing the building materials, in renovation, refurbishment and demolition processes of the buildings. This includes initial embodied energy, recurrent embodied energy and demolition energy. Initial embodied energy is consumed during production of materials and components and includes raw material procurement, building material manufacturing and finished product delivery to the construction site. Recurrent embodied energy is used in various maintenance and refurbishment processes during the useful life of a building. Demolition energy is expended in processes of building's deconstruction and disposal of building materials.

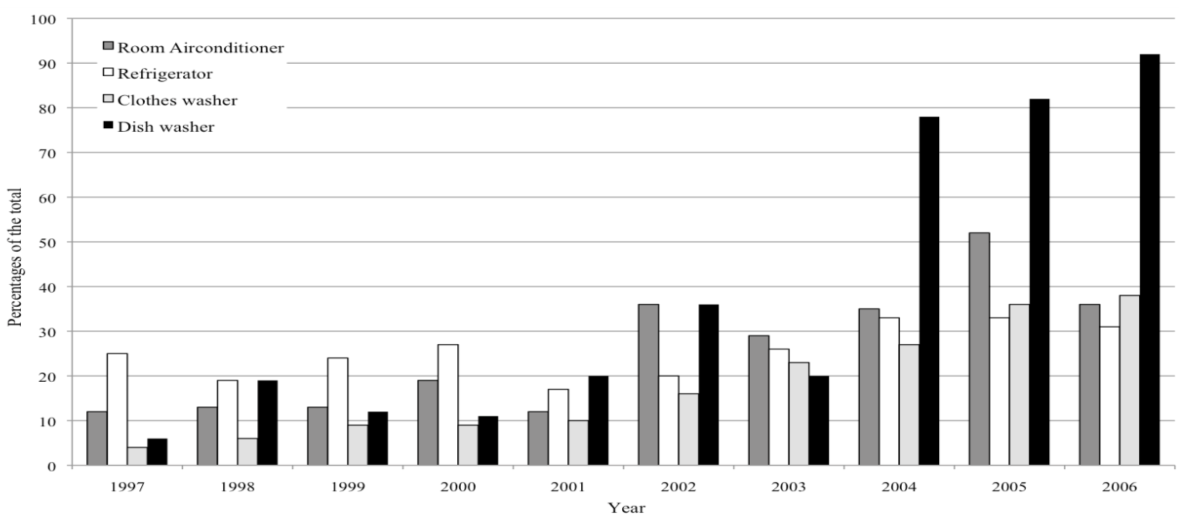


Figure 1: Growing number of Energy Star approved home appliances (based on USDOE 2008 data

## 3.3. Significance of embodied energy

Until recently, the emphasis of energy conservation research was on the operating energy of a building. However, current research disproved this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy (Crawford and Treloar, 2003; Crowther, 1999; Pullen et al., 2006). Operational energy conservation could be accomplished with energy efficient appliances and advanced insulating materials, which are available more readily (Nassen et al., 2006; Sartori and Hestnes, 2007; Ding, 2004). For example, an increase is observed in the number of Energy Star labeled home appliances in the United States over a ten-year span (see figure 1), which could reduce operating energy gradually (US Department of Energy, 2008). However, preferring low energy intensive materials can only reduce the embodied energy. Commonwealth Scientific and Industrial Research Organization (CSIRO) research has demonstrated that the embodied energy content of an average household in Australia is nearly equivalent to 15 years of operational energy (Commonwealth of Australia, 2005). Crawford and Treloar (2003) insinuate that, in Australia, the embodied energy contained in a building is 20 to 50 times the operational energy needed for the building annually.

*Table 1: Embodied energy figures, showing variability, derived by various authors (Source - Ding [7])*

| *Embodied Energy (GJ/$m^2$)* | *Building Type* | *Source* |
|---|---|---|
| *3.6* | *Residential* | *Hill, 1978 (cited by Pullen, 2000b)* |
| *3.9* | *Residential* | *Edwards et al., 1994* |
| *4.3 – 5.3* | *Residential* | *D' Cruz et al., 1990 (cited by Pullen, 2000b)* |
| *4.9* | *Residential* | *Pullen, 1995* |
| *5.0* | *Residential* | *Lawson, 1992 (cited by Pullen, 2000b)* |
| *5.9* | *Residential* | *Pullen, 2000b* |
| *6.6* | *Residential* | *Ballantyne et al., 2000 (cited by Pullen, 2000b)* |
| *6.8* | *Residential* | *Treloar 1998* |
| *8.76* | *Residential* | *Treloar 1996b* |
| *3.4 – 6.5* | *Commercial* | *Honey and Buchanan, 1992 (cited by Pullen, 2000c)* |
| *4.3 – 5.1* | *Commercial* | *Cole and Kernan, 1996* |
| *5.5* | *Commercial* | *Oppenheim and Treloar, 1995* |
| *8.0 – 12.0* | *Commercial* | *Oka et al., 1993 (cited by Pullen, 2000c)* |
| *8.2* | *Commercial* | *Tucker and Treloar, 1994 (cited by Pullen, 2000c)* |
| *10.5* | *Commercial* | *Yohanis and Norton, 2002* |
| *18.6* | *Commercial* | *Stein et al., 1976 (cited by Pullen, 2000c)* |
| *19.0* | *Commercial* | *Tucker et al., 1993 (cited by Treloar, 1996b)* |

## 3.4. Variation and inconsistency in embodied energy measurement results

Buchanan and Honey (1994); Crowther (1999); Crawford and Treloar (2003); Ding (2004); Horvath (2004); Crawford and Treloar (2005); Nassen et al. (2007); and Langston and Langston (2008) suggest that the embodied energy results from research studies show significant variation in embodied energy figures, which are derived from information from disparate sources and different countries. Ding (2004) present embodied energy figures derived by various research studies that demonstrate variations in embodied energy figures of a typical residential unit and a commercial building (see table 1). The mean of residential units' embodied energy is 5.506 and standard deviation is found to be 1.56, while commercial buildings' embodied energy figures demonstrate a mean of 9.19 and a standard deviation of 5.4. This indicates that the commercial buildings show greater variability than the residential units in embodied energy terms (see figure 2 and 3).

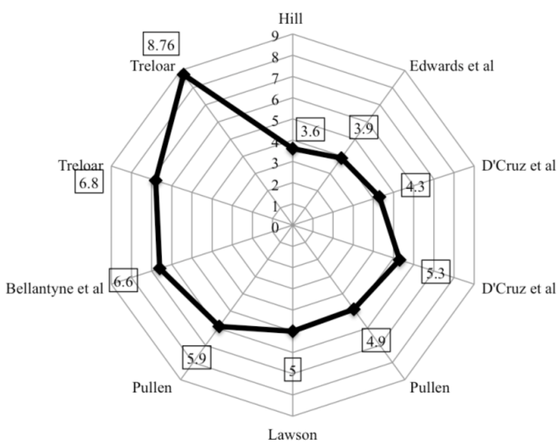


Figure 2: Differing embodied energy figures in residential buildings (based on Ding, 2004)

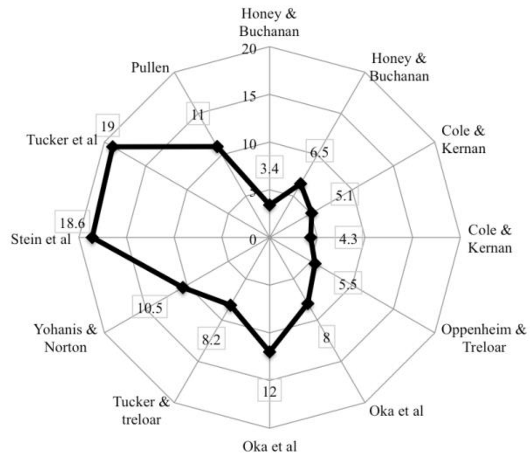


Figure 3: Differing embodied energy figures in commercial buildings (based on Ding 2004)

## 4. Findings: factors causing variation and inconsistency

The literature search suggests 10 parameters that are responsible for affecting the quality of embodied energy results adversely. These parameters are presented in the form of a matrix along with the research studies supporting them (see Table 2). Life Cycle Analysis (LCA) is referred at various places in the following paragraphs, as embodied energy analysis is a part of LCA. Following section describes these parameters in brief.

### 4.1. System boundary

In past embodied energy analysis, whenever it becomes difficult to acquire necessary reliable and consistent information, a boundary is drawn and further analysis in upstream is truncated (Crawford and Treloar, 2003). This boundary defines the number of energy and material inputs that are considered in the embodied energy calculation and could include stages such as raw material extraction in distant upstream and demolition and disposal in farthest downstream. Research studies have adopted different system boundaries and, as a result, their measurement figures vary and could not be compared (Miller, 2001; Ding, 2004; Horvath, 2004; Lenzen, 2001).

*Table 2: Matrix of parameters causing variation and authors*

| *Authors and Year of Study/ Research* | *Parameters* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *(1) System B* | *(2) Method of EE Analysis* | *(3) Geographic Location* | *(4) Primary and Delivered Energy* | *(5) Age of Data* | *(6) Data Source* | *(7) Completeness of data* | *(8) Manufacturing Technology* | *(9) Feedstock Energy Consideration* | *(10) Temporal Representation* |
| *Buchanan and Honey, 1994* | | | √ | | √ | | | √ | | |
| *Pears, 1996* | | √ | | √ | | √ | | √ | | |
| *Pullen, 1996* | | √ | √ | | | √ | √ | | | |
| *Alcorn and Wood, 1998* | | | √ | | √ | √ | √ | | | √ |
| *Lippiatt, 1999* | | | √ | | | | | √ | | √ |
| *Pullen, 2000a* | | | | √ | | | | | | |
| *Pullen, 2000 b* | | √ | √ | | √ | | | √ | √ | |
| *Treloar et al., 2001a* | | √ | √ | √ | | | | √ | | |
| *Miller, 2001* | √ | √ | | | | | | | | |
| *Glover et al., 2002* | √ | | | | | | | | | |
| *Junnila and Horvath, 2003* | √ | | √ | | | √ | | | | √ |
| *Ding, 2004* | √ | | √ | | √ | √ | | | | |
| *Horvath, 2004* | √ | √ | | | | | | | | |
| *Suh et al., 2004* | √ | | | | | | | | | |
| *Crawford and Treloar, 2005* | | √ | | | | | | | | |
| *ISO 14040, 2006* | √ | | √ | | √ | | √ | √ | √ | √ |
| *Lenzen, 2006* | √ | | √ | | √ | | | √ | | √ |
| *Holtzhausen, 2007* | | √ | √ | | | | | √ | | |
| *Menzies et al., 2007* | | | √ | | √ | √ | √ | √ | | |
| *Nassen et al., 2007* | | √ | | | | | | | | |
| *Sartori and Hestnes, 2007* | | | √ | √ | | √ | | | √ | |
| *Hammonds and Jones, 2008* | √ | √ | √ | | √ | | | | | |
| *Peereboom et al., 2008* | | | √ | | √ | √ | | √ | | √ |

## 4.2. Methods of embodied energy measurement

Process analysis, statistical analysis, input output analysis and hybrid analysis are among the major methods used for embodied energy computation (Ding, 2004; Alcorn and Baird, 1996; Lenzen, 2001; Treloar, 1998; Crawford and Treloar, 2003; Fay and Treloar, 1998; Pullen, 2000 b). These methods possess different limitations and their level of accuracy varies. As a result their embodied energy results differ and cannot be juxtaposed (Pullen, 2000 b; Miller, 2001; Treloar et al., 2001a; Horvath, 2004; Crawford and Treloar, 2005; Nassen et al., 2007).

## 4.3. Geographic location of the study

Research studies performed in different countries differ from one another in term of data relating to raw material quality, production processes, economy, delivered energy generation, transportation distances, energy use (fuel) in transport, and human labor. This eventually affects the determination of energy consumption and their results vary radically (Buchanan and Honey, 1994; Ding, 2004; Lenzen, 2001; Sartori and Hestnes, 2007; Lawson, 1996; Pears, 1996; Pullen, 1996). Processes of industrial and economic sectors differ greatly and thus influence the calculated embodied energy values (Buchanan and Honey, 1994). Different locations of data could affect the embodied energy results because of variations in production processes and energy tariffs (Pullen, 2000 b).

## 4.4. Primary and delivered energy

Primary energy is defined as “the energy required from nature (for example, coal) embodied in the energy consumed by purchaser (for example, electricity)” and delivered energy is defined as “the energy used by the consumer” (Fay and Treloar, 1998; Fay et al., 2000). The measurements of embodied energy are consistent if those are based on primary energy (Fay and Treloar, 1998), but if the delivered energy is considered, the results could be misleading and ambiguous (Fay and Treloar, 1998; Sartori and Hestnes, 2007). Furthermore, both the operating and embodied energy must be measured in terms of primary energy consumption in order to attain consistency and to acquire the most appropriate environmental implications (Fay and Treloar, 1998).

## 4.5. Age of data sources

Research studies based on old and current data sources could differ significantly as a result of changing technology of manufacturing and transportation. Consideration of old transportation energy data could affect the energy values, as new vehicles have more fuel efficiency and a different fuel structure. Any study that is based on such conflicting data sources could be misleading and uncertain (Peereboom et al., 1998; Alcorn and Wood, 1998)). Building material performance and material production efficiency will be enhanced over time and could be responsible for variations in measurement figures (Buchanan and Honey, 1994; Crawford and Treloar, 2003; Pullen 2000b). Hammonds and Jones (2008) attempt to consider current data sources in establishing the inventory of carbon and energy because of their relevance, certainty and temporal representativeness.

## 4.6. Source of data

Research studies use data that are collected using different approaches. Some studies derive their own data by calculating the energy intensiveness while; some utilize energy figures calculated by other studies. This subjective selection of data influences the final results significantly (Ding, 2004; Junnila and Horvath, 2003). Peereboom et al. (1998) suggests that practitioners of Life Cycle Analysis (LCA) rely on various sources of information and do not have access to primary data that leads to uncertainty and variability in LCA results. Data source is an important parameter, and its reliability, uncertainty, and transparency must be considered when performing LCA (Alcorn and Wood, 1998; Lenzen, 2001).

## 4.7. Data completeness

According to Menzies et al. (2007) and Peereboom et al. (2008), research studies often could not access primary data sources and rely on secondary data sources that may or may not be complete. This incompleteness is due to either the limitations of calculation method or subjective selection of system boundaries. Menzies et al. (2007) assert that, the accessibility of data, methodology adopted, and selection of system boundaries govern the completeness of data could affects the reliability of end results significantly. Alcorn and Wood (1998) suggest that the completeness of data needs to be considered while choosing one material dataset over another.

## 4.8. Technology of manufacturing processes

Differing technologies of material manufacturing possess varied level of energy consumption, as advanced technology could consume less energy due to energy efficient processes. In the similar geographic location and during the same time period, two studies could generate different results if they are extracting information from two material manufacturers using different technologies (Pears, 1996). Technological representativeness is an important quality of data that should be taken into account in order to eliminate inconsistency and variability of results (Peereboom et al., 1998; Holtzhausen, 2007; Lippiatt, 1999; Menzies et al., 2007; Lenzen, 2001).

## 4.9. Feedstock energy consideration

Feed stock energy is the energy embedded in the ingredients used in the process of manufacturing a material. Petrochemicals like oil and gas are used as a material input in the manufacturing process of products like plastics and rubber. Feed stock energy needs to be considered in the calculation of the total embodied energy in a material (Hammonds and Jones, 2008). Inclusion of feed stock energy in embodied energy calculation or LCA could cause variations in embodied energy figures, and such figures are not comparable across research studies (Pullen, 2000b).

## 4.10. Temporal representativeness

A significant data quality indicator in Embodied energy analysis and LCA is temporal representation (Junnila and Horvath, 2003; Peereboom et al., 1998; Alcorn and Wood, 1998; Weidema et al., 1996). Some of the energy studies are based on recently developed technology, and some studies consider a mix of new and old technology (SAIC, 2006). The end results of such studies differ and are not consistent.

This list of parameters is not exhaustive and may include more factors that are responsible for variations. Alcorn and woods (1998) and Peereboom et al. (1998) do not rule out possibility of existence of other parameters.

## 4.11. Current standards: issues of conflict

There exist a set of standards for the process of LCA derived by International Standardization Organization (ISO). The first effort to standardized LCA came with the publication of “a code of practice” by Society of Environmental Toxicology and Chemistry (SETAC) in 1993. This document later formed the basis of ISO standards such as ISO 14040 and ISO 14044 (Berkhout, 1996; McDougall and Hruska, 2000). Owens (1996) asserts that the ability of SETAC code is questionable in explaining interaction between the study system and the environment. Ayres (1995) asserts that the methodology for LCA described by, both the ISO standards and SETAC code, is flawed. Researchers like Weidema et al. (2008), Zamagni et al. (2008), Reap et al. (2008), Suh et al. (2009), Rebitzer et al (2004) and Raynolds et al. (2000) point out the problems associated with the issues of system boundaries and allocation in current ISO standards for LCA. Referring to literature regarding critical reviews of SETAC and ISO standards identifies following issues.

**System boundaries**: there is a lack of clarity, subjectivity and issue of truncation error in the current selection criteria and procedures mentioned by LCA standards (Weidema et al., 2008; Zamagni et al., 2008; Reap et al., 2008; Suh et al., 2009; Rebitzer et al., 2004; Raynolds et at., 2000).

**Allocation:** It is still unclear which approach must be adopted for the purpose of allocation as there is disagreement regarding current approaches. The feasibility of the current method of allocation is questionable according to critiques (Weidema et al., 2008; Zamagni et al., 2008; Reap et al., 2008; Suh et al., 2009; Rebitzer et al., 2004; Raynolds et at., 2000).

**Methodology for embodied energy calculation**: the literature suggests that the methodology prescribed by the LCA standards is still unclear (Curran and Young, 1996; Smith and Peirce, 1996; Trusty, 2004; Zamagni et al., 2008); and

**Sensitivity and uncertainty analysis**: according to the literature, the current standards mention conducting a sensitivity and uncertainty analysis but fail to provide an appropriate method for performing this analysis (Reap et al., 2008; Zamagni et al., 2008; Ross et al., 2002).

## 5. Conclusions

The current environmental practices such as environmental selection of building materials, eco-labeling, and green building assessment, in the construction industry, depend mainly on the results of LCA of the buildings. Embodied energy analysis is an integral part of the process of LCA. The literature suggests that the results of neither embodied energy calculation nor LCA are valid and comparable. Therefore, these environmental practices can no longer fulfill their sustainability and energy efficiency goals accurately. The lack of comparability of the energy intensiveness of two building materials or products seriously hampers the process of selecting low-energy building materials and products. The literature indicates that there is a stated need to adapt a tradition of selecting building materials that are low energy intensive. However, given the incomparable and differing embodied energy data, a decision to select a material no longer remains valid.

The ISO, SETAC, and the American Society for Testing and Materials (ASTM) are among pioneer institutions that are responsible for advancements in standardization and scientific development of LCA. However, literature suggests that LCA studies that follow current standards have differing results. Moreover, the critical appraisal of these standards suggests the need for major improvements and modifications in their current status. The literature in the field of embodied energy analysis reveals that there exist no standards that can address the problems of embodied energy calculation and there is a strong need to develop a protocol or standard that can be utilized for embodied energy analysis. This paper identifies the urgent need to establish a protocol to standardize and guide the process of embodied energy analysis and recommends that this protocol needs to address the issues identified by this paper. Research studies discussed in the paper have stated the need to introduce standardization and global comparability to analysis of EE in building materials. Future research endeavors can focus on the creation of a protocol that facilitates a reliable, consistent, comparable, and current database of EE.

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