

## Identification of parameters for embodied energy measurement: A literature review

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### ABSTRACT

The building construction industry consumes a large amount of resources and energy and, owing to current global population growth trends, this situation is projected to deteriorate in the near future. Buildings consume approximately 40 percent of total global energy: during the construction phase in the form of embodied energy and during the operation phase as operating energy. Embodied energy is expended in the processes of building material production (mining and manufacture), on-site delivery, construction and assembly on-site, renovation and final demolition. Recent studies have considered the significance of embodied energy inherent in building materials, with a specific focus on this fraction of sequestered energy. Current interpretations of embodied energy are quite unclear and vary greatly, and embodied energy databases suffer from problems of variation and incomparability. Furthermore, there is no reliable template, standard or protocol regarding embodied energy computations that could address these problems in embodied energy inventories. This paper focuses on the analysis of existing literature in order to identify differing parameters so that development of a consistent and comparable database can be facilitated.

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### 1. Introduction

The construction industry, along with its support industries, is one of the largest exploiters of natural resources, both renewable and non-renewable, that is adversely altering the environment of the earth [1–6]. It depletes two-fifths of global raw stone, gravel, and sand and one-fourth of virgin wood, and consumes 40 percent of total energy and 16 percent of water annually [3,7–10]. Fig. 1 shows the percentage share of building's energy consumption over the span of eight years and its anticipated growth trends by the end of 2030. The anticipated growth in global population from 6.5 billion in 2005 to approximately 9.0 billion in 2035 [11] indicates the grave situation of material and energy consumption as a result of the anticipated increase in construction activities. The construction sector, in particular, is one of the largest consumers of commercial energy in the form of electricity or heat by directly burning fossil fuels [1]. Urge-Vorsatz and Novikova [8] assert that, during 2004, buildings alone depleted nearly 37 percent of the world's energy and this figure is anticipated to reach 42 percent by 2030. Construction activities not only con-

sume energy, but also cause environmental pollution and emission of greenhouse gases, which lead to climate change. Therefore, it is urgent to review, as well as modify, current construction practices such as design and engineering methods, construction techniques and manufacturing technology to tame energy consumption.

The total life cycle energy of a building includes both embodied energy and operating energy [7,12]:

- (1) *Embodied energy (EE)*: sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal; and
- (2) *Operating energy (OE)*: expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

Until recently, only operating energy was considered, owing to its larger share in the total life cycle energy. However, due to the advent of energy efficient equipment and appliances, along with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current emphasis has shifted to include embodied energy in building materials [7,12–16]. Ding [7] suggests that the production of building components off-site accounts for 75 percent of the total energy embedded in buildings [1] and this share of energy is gradually increasing as a result of the increased use of high energy inten-

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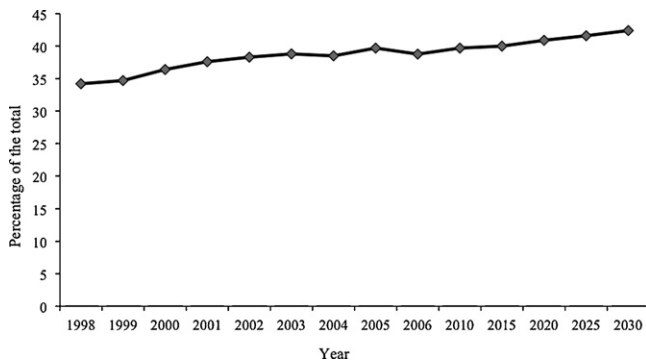


Fig. 1. US energy consumption in building sector as percent of total (derived from US Dept. of Energy data).

sive materials [9,13]. Thus, there is a genuine demand to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce energy consumption [9,17]. At a macro-level, proper accountability of embodied and operating energies will contribute to data and information needed to create an energy economy that accounts for indirect and direct contributions.

Langston and Langston [9] suggest that, while measuring operating energy is easy and less complicated, determining embodied energy is more complex and time consuming. Furthermore, there is currently no generally accepted method available to compute embodied energy accurately and consistently [12,18] and as a result, wide variations in measurement figures are inevitable, owing to various factors [7,9,12,18,19].

## 2. Embodied energy analysis—current state of research

### 2.1. Interpretation of embodied energy

Buildings are constructed with a variety of building materials and each material consumes energy throughout its 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. The energy consumed in production (in conversion and flow as proposed by Koskela [20]) is called the “embodied energy” of the material and is the concern of energy consumption and carbon emissions. Gonzalez and Navarro [21] assert that building materials possessing high-embodied energy could possibly result in more carbon dioxide emissions than would materials with low embodied energy.

According to Miller [18], the term “embodied energy” is subject to various interpretations rendered by different authors and its published measurements are found to be quite unclear. Crowther [12] defines embedded 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. [22] state, “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).” Another characterization given by Boustead and Hancock (as cited by Langston and Langston [9]) is, “Embodied energy is defined as the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like. . .” Likewise, a more comprehensive definition, provided by Baird, 1994; Edwards and Stewart, 1994; Howard and Roberts, 1995; Lawson [56]; Cole and Kernan,

1996 (as cited in Ding [7]), explains 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 differences of opinion about the system boundaries to be included in embodied energy analyses.

### 2.2. Embodied energy modeling

Overall, buildings use the following types of energy consumption (see Fig. 2), from raw material extraction to deconstruction and disposal [7,23,24].

#### 2.2.1. Direct energy [7,23,24]

Direct energy is consumed in various on-site and off-site operations like construction, prefabrication, transportation and administration.

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

#### 2.2.2. Indirect energy [7,23,24]

Indirect energy is mostly used during the manufacturing of building materials, in the main process, upstream processes and downstream processes and during renovation, refurbishment, and demolition.

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

### 2.3. Significance of embodied energy

As mentioned earlier, until recently, major endeavors for energy conservation assumed the operating energy of a building to be much higher than the embodied energy of a building. However, current research has disproven this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy [12,25,26]. Embodied energy is expended once in the initial construction stage of a building, while operational energy accrues over the effective life of the building. Operational energy conservation could be accomplished more optimally with energy efficient appliances and advanced insulating materials, which are available more readily [7,13,16]. Fig. 3 indicates the growing number of Energy Star labeled home appliances in the United States over a ten-year span, which is one factor that could reduce operational energy in buildings over time [27].

Embodied energy can only be reduced by preferring low energy intensive materials. Commonwealth Scientific and Industrial Research Organization (CSIRO) research has demonstrated that the embodied energy contents of an average household in Australia

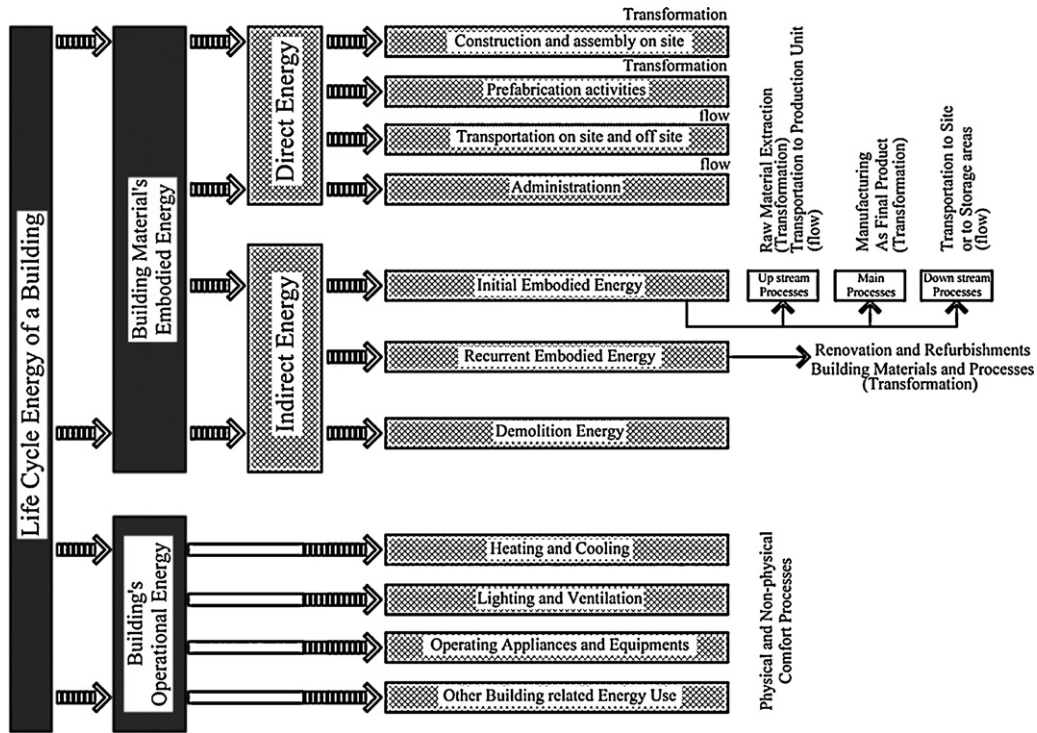


Fig. 2. Embodied energy modeling.

are nearly equivalent to fifteen years of operational energy [28]. Crawford and Treloar [25] suggest that, in Australia, the embodied energy contained in a building is 20–50 times the annual operational energy needed for the building.

A modest knowledge and awareness of the embodied energy contents of building materials could encourage the use of not only production and development of low embodied energy materials, but also their preference among construction design and industry to curb energy use and carbon dioxide discharge [7]. The building material (production) industry is responsible for 20 percent of the world's fuel consumption, therefore, embodied energy results are critical for national and global strategic plans for energy [29].

### 3. Embodied energy analysis—problem of variation and inconsistency

#### 3.1. Current research efforts

##### 3.1.1. Framework of measurement

Treloar [23] performed a thorough study to create a comprehensive framework for embodied energy analysis that avoids the earlier incompleteness of process analysis and unreliability of input/output-based analysis. Furthermore, he asserted that process and input/output-based hybrid analysis have few unwanted indirect effects that influence the reliability of measurements. Treloar [23] concludes that a new method of analysis is needed in order to

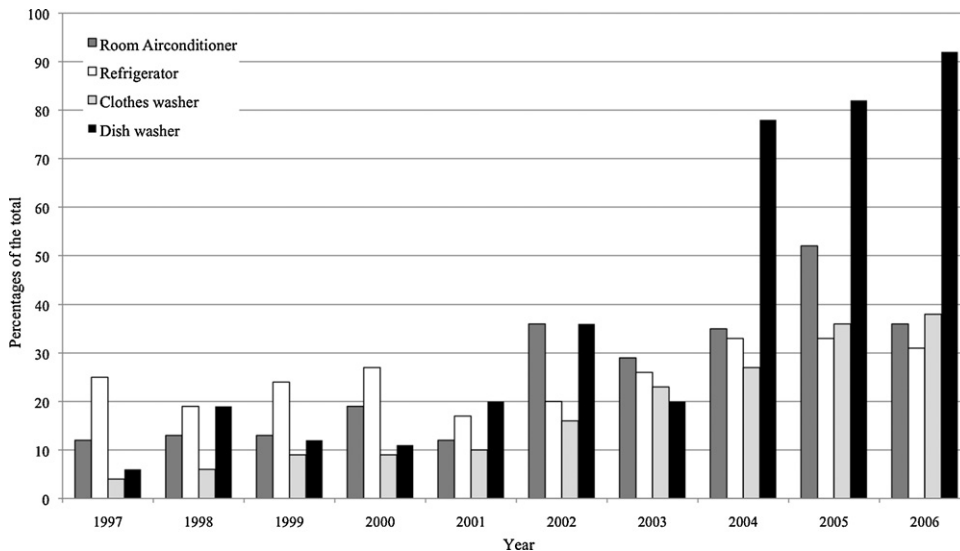


Fig. 3. Indication of growing number of Energy Star rated home appliances in the United States (derived from US Dept. of Energy Data Book, 2008).

address this problem. He presented an improved comprehensive framework of analysis as a research thesis for his doctoral program, which he claims can be used to measure embodied energy of building materials, as well as building components, accurately and completely.

### 3.1.2. Embodied energy inventory

Current embodied energy inventories use currently available methods of embodied energy measurements and reliable or unreliable data, to calibrate energy consumed during the manufacture of a building material or a component. The methods of measurement have pros and cons that are discussed later in this paper. Hammond and Jones [30] of the Department of Mechanical Engineering, University of Bath, United Kingdom, are performing analysis of building materials to establish an inventory of carbon and energy for a carbon vision buildings program. They have established the most recent list of not only energy intensities of a variety of building materials, but also respective carbon implications associated with their production process. They have adopted a “cradle to gate” approach, which considers all energy consumption from upstream stages such as raw material extraction to the final stage as a finished product. Some calculations of embedded energy have taken into account the energy consumed during delivery of these products to construction-sites with a much wider system boundary; however, these are few in number. Alcorn and Baird [31] of the Center for Building Performance and Research at Victoria University of Wellington, New Zealand has evolved a coefficient of carbon emission and a database of embodied energy of building materials, which are used in New Zealand. He considered a process-based hybrid analysis method for the computation to avoid incompleteness and unreliability. Buchanan and Honey [32] refer to energy coefficient data in a report prepared by Baird and Chan (1983), in order to provide a comprehensive list of energy and carbon dioxide emission data to show implications of construction activities. Adalberth [33,34], Pullen [35], Crawford and Treloar [36] and Lenzen et al. [37] made noteworthy endeavors to ascertain the amount of sequestered energy in selected building materials.

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

Buchanan and Honey [32]; Crowther [12]; Crawford and Treloar [25]; Ding [7]; Horvath [3]; Crawford and Treloar [36]; Nassen et al. [16]; and Langston and Langston [9] suggest that the embodied energy results from research studies show significant variation in embodied energy figures, which are derived by information from disparate sources and different countries. Table 1 indicates variation in various embodied energy figures of a typical residential unit and a commercial building derived by different research studies (source Ding [7]). Figs. 4 and 5 represent these variations graphically through a radar diagram and point out that residential and commercial units differ in terms of embodied energy. The mean of residential units' embodied energy is  $5.506 \text{ GJ/m}^2$  and standard deviation is found to be  $1.56 \text{ GJ/m}^2$ , while commercial buildings' embodied energy figures demonstrate a mean of  $9.19 \text{ GJ/m}^2$  and a standard deviation of  $5.4 \text{ GJ/m}^2$ . This indicates that commercial buildings show greater variability than do residential units in embodied energy terms. The literature suggests that determination of embodied energy is difficult and no standard methodology is available to estimate the energy level of building materials [12]. It is relatively easy to configure operating energy of buildings, however, embodied energy determination is more time consuming and complex [9].

Amidst several efforts to calculate embodied energy, some noteworthy attempts have been made to figure out possible errors

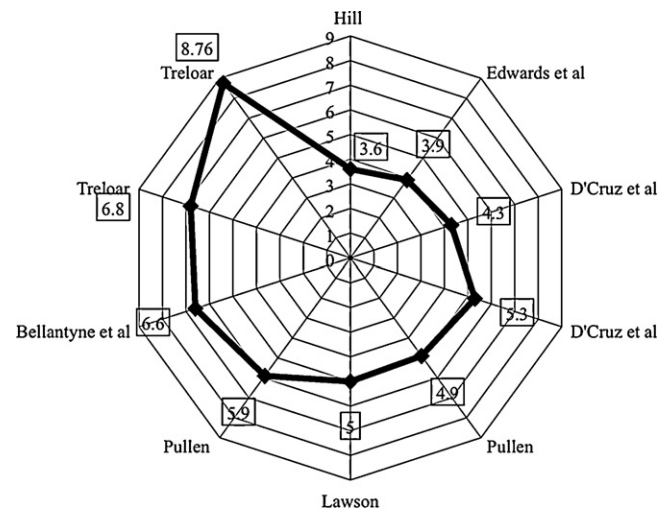


Fig. 4. Differing embodied energy values in residential buildings.

and difficulties associated with these measurements. Pears, 1996 (as cited by Ding [7]) asserts that different information sources and inclusion of primary and secondary energy figures could bring 30–40 percent variation in measurement figures. Lenzen [19] warns of a possible truncation error in conventional process analysis, which could lead to a limit of 50 percent depending upon the product and its process under consideration. The incompleteness in such methods of embodied energy analysis could be as large as 20 percent (Treloar, 1997, as cited by Langston and Langston [9]). In addition to these concerns, Pullen [38] observes that process analysis does not include upstream processes (raw materials extraction and transportation) and some downstream processes (transporting finished products to construction-sites) and, thus, its results are not consistent.

## 4. Research method

The research method adopted for this study includes a literature review and derives its conclusions from referring to various peer reviewed and published bibliographic sources. This research

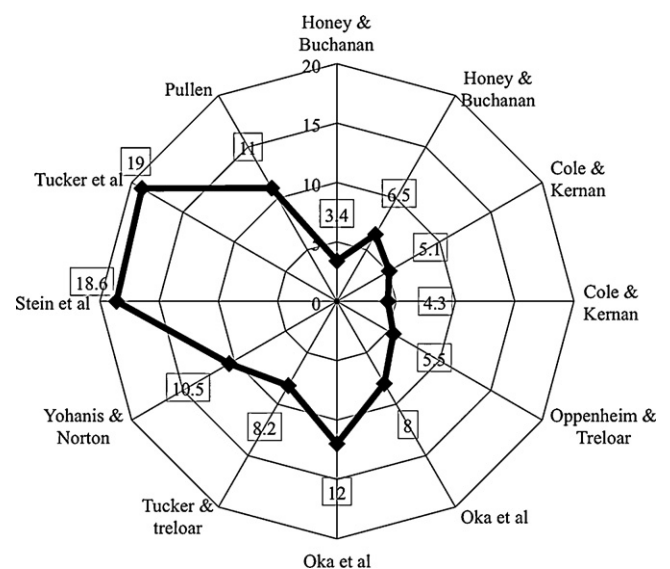


Fig. 5. Differing embodied energy values in commercial buildings.

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

Embodied energy (GJ/m <sup>2</sup> )	Building type	Source
3.6	Residential	Hill (1978) (cited by Pullen [38])
3.9	Residential	Edwards et al. (1994)
4.3–5.3	Residential	D' Cruz et al. (1990) (cited by Pullen [38])
4.9	Residential	Pullen (1995)
5.0	Residential	Lawson (1992) (cited by Pullen [38])
5.9	Residential	Pullen [38]
6.6	Residential	Ballantyne et al. (2000) (cited by Pullen [38])
6.8	Residential	Treloar [24]
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)

method is called 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 [39]. The concept of LBD demonstrates great potential that has been widely acknowledged by research communities [39–44]. 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 [39,41].

The data interpretation is performed using the concept of triangulation that involves cross-referencing various sources of information about the same phenomenon. This paper applies a similar approach by referring to various literature sources in order

to identify parameters that are causing variations in the embodied energy database. After the parameters and their respective sources are identified, the information is arranged in the form of a matrix.

**5. Findings: factors responsible for variation and inconsistency**

The literature search revealed 10 parameters that influence the quality of embodied energy results. Table 2 presents a matrix that shows these parameters along with the research studies supporting them. These parameters are described in detail in the following paragraphs.

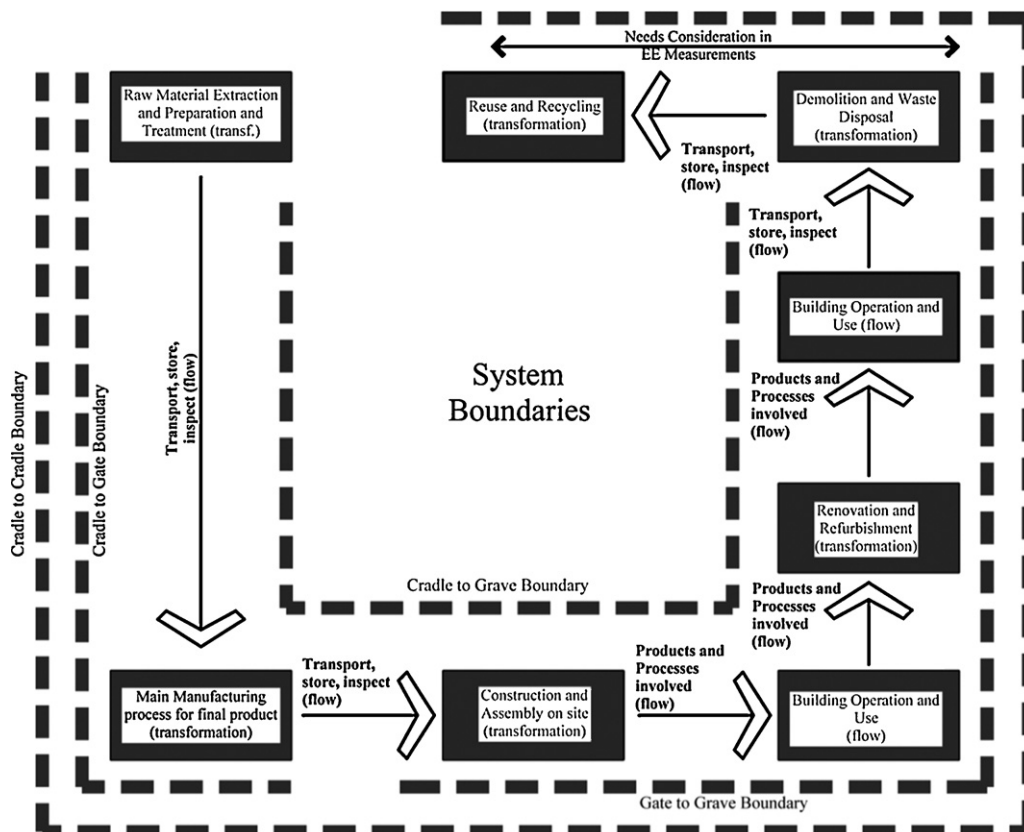


Fig. 6. System boundaries in the life cycle of a building material.

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

Authors and year of study/research	Parameters	(1) System boundaries	(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 [32]				✓					✓		
Pears [49]	✓								✓		
Pullen [50]	✓		✓	✓	✓	✓	✓		✓		✓
Alcorn and Wood [51]				✓	✓	✓	✓		✓		✓
Lippiatt [10]				✓					✓		
Pullen [35]			✓	✓					✓		
Pullen [38]			✓	✓					✓		
Treloar et al. [17]			✓	✓					✓		
Miller [18]	✓										
Glover et al. [52]	✓										
Junnila and Horvath [46]	✓			✓	✓						✓
Ding [7]	✓			✓							
Horvath [3]	✓			✓							
Suh et al. [45]	✓										
Crawford and Treloar [36]	✓										
ISO 14040 [53]	✓										
Lenzen [19]	✓			✓			✓		✓		✓
Holtzhausen [2]	✓			✓					✓		✓
Menzies et al. [54]	✓			✓					✓		✓
Nassen et al. [16]	✓			✓					✓		✓
Sartori and Hesmes [13]	✓			✓					✓		✓
Hammonds and Jones [55]	✓			✓					✓		✓
Peereboom et al. [47]	✓			✓					✓		✓

5.1. System boundaries

In past embodied energy analyses, whenever it became difficult to acquire the necessary reliable and consistent information, a boundary was drawn and further analysis in upstream was truncated [25]. These boundaries could range from raw material extraction in distant upstream to demolition and ultimate disposal furthest downstream (Fig. 6). Authors adopted various system boundaries and, as a result, measurement figures varied and could not be compared [3,7,18,19].

Exclusion of certain energy inputs in building components, such as furniture and fittings, and in processes, such as on-site construction and demolition, can cause large variations in embodied energy results [7]. Boundary definition is one of the most critical issues that cause the exclusion of upstream processes that could make a considerable difference in embodied energy calculations [3]. Miller [18] asserts that published embodied energy results differ significantly; furthermore, there is no explanation about what is included or excluded in the calculation.

Lenzen [19] points out a possible truncation error that is caused by truncating system boundaries in upstream processes of a product's life cycle. Such differing assumptions about boundaries result in differing quality of data, thus making the data incomparable. Suh et al. [45] state that subjective selection of system boundaries could render end results invalid and with such selection of boundaries, comparative evaluation of two products cannot be guaranteed [46]. Peereboom et al. [47] not only propose a method to select the system boundaries, but also to analyze the influence of such differing parameters, which is found to be 10–100 percent. Raynolds et al. [48] note the need for a consistent system boundary selection method so that comparative assessment would be possible.

5.2. Methods of embodied energy analysis

Among the major processes of embodied energy analysis are process analysis, statistical analysis, input/output analysis and hybrid analysis [7,19,23–25,38]. Results of disparate embodied energy and life cycle analysis methods differ widely, due to respective inherent limitations and, thus, cannot be juxtaposed [3,16–18,36,38]. The following information elaborates on the advantages, limitations and error levels of the three most widely used methods of embodied energy analysis.

5.2.1. Process-based analysis

Process-based analysis is one of the most widely used methods of embodied energy (EE) analysis, as it delivers more accurate [7] and reliable results [25,31,38]. The process commences with the building material as a final product and works backward in the upstream of main process, taking into account all possible direct energy inputs or sequestered energy of each contributing material [24,31].

However, process analysis is ascertained to be impracticable and incomplete because of the exclusion of many upstream processes, as a result of truncation of system boundaries. This occurs because of the enormous efforts required to identify and quantify each small energy and product input of the complex upstream process [7,22,31,36]. The magnitude of system incompleteness and error in process analysis is estimated to be as high as 50 percent and 10 percent respectively, and even inventories based on detailed and extensive process analysis fail to attain significant completeness [22,36]. Pullen [38] states that process analysis fails to capture not only some of the downstream processes, but also the capital energy inputs of plants and equipment required in the course of building material production.

### 5.2.2. Input/output-based analysis

An input/output-based analysis could account for most direct and indirect energy inputs in the process of production of building materials and thus is considered relatively complete [23]. This process makes use of economic data of money flow among various sectors of industry in the form of input/output tables made available by the national government, thereby transcribing economic flows into energy flows by applying average energy tariffs [7,23–25,31,38]. Thus, in an input/output analysis, the EE is calculated by multiplying the cost of the product by the energy intensity of that product expressed in MJ or GJ/\$1000 and dividing it by \$1000 [36].

This method is assumed to be comprehensive and complete as it embraces nearly the entire system boundary. However, it also suffers from inherent problems such as assumption of homogeneity and proportionality, errors and uncertainty of economic data for example energy tariff and product cost, and aggregation and grouping of sectors. These problems make its results erroneous and unreliable [23–25,38], and error in the measurement figures can range up to 50 percent [17].

### 5.2.3. Hybrid analysis

A hybrid analysis is devised by unifying the benefits of the two methods, to eliminate fundamental errors and limitations of both process and input–output-based analyses. However, these methods need to be compared and validated [25]. The hybrid method starts with process analysis of readily available energy input data of the final production stage and likely, one stage more in the upstream and then substitutes it with the input/output method when it is difficult to achieve reliable and consistent information regarding complex upstream processes [19,31]. Treloar [24] categorizes this method into two types:

*Process-based hybrid analysis* (see Fig. 7): This method assimilates input/output-based analysis to complex parts of upstream processes of material production and thus obviates the incompleteness inherent in process analysis. However, complex materials, which involve more than one material, could pose problems for this method. Furthermore, overestimated prices of products could also distort the results [24].

*Input/output-based hybrid analysis* (see Fig. 8): This method incorporates identification and extraction of direct energy paths from input/output-based analysis in order to integrate the reliable and accurate process based data to avoid indirect effects [24].

According to Treloar (as cited by Langston and Langston [9]), the incompleteness or error in typical embodied energy calculation and analysis is approximately 20 percent and thus no method is available that is fully efficient, however, input–output-based hybrid analysis is considered complete and nearly perfect in the life cycle analysis of buildings [9,25,31].

### 5.3. Geographic location of study area

Countries in the studies differ from one another in not only geographic and climatic characteristics, but also in raw material quality, production processes, economic data, processes of delivered energy generation, transport distances, energy use (fuel) in transport, and labor. This eventually affects the end results of energy use analysis, which vary radically [7,13,19,32,49,50,56]. Processes of industrial and economic sectors differ greatly and thus influence the calculated embodied energy values [32]. Different locations of data could affect the embodied energy results because of variations in production processes and energy tariffs [38]. Countries could differ in fuel supply structure and thus studies in those locations could produce different energy values [57]. Sartori and

Hestnes [13] assert that because of varying climate, types of building, types of construction, and assumptions about indoor climate, various geographic locations eventually cause incomparability and inconsistency in energy results. Representativeness of geographic location is a pivotal element that should be considered while computing embodied energy values [2,10]. Differing energy tariffs paid by different material manufacturers at various locations could lead to a possible error of 2.6 percent in embodied energy results if they are derived using the input/output method [50]. Countries have differing material prices that could result in an error of 2 percent in embodied energy results [50].

### 5.4. Primary and delivered energy

Fay and Treloar [23] and Fay et al. [58] define primary energy as “the energy required from nature (for example, coal) embodied in the energy consumed by the purchaser (for example, electricity)” and delivered energy as “the energy used by the consumer.” If information is based upon primary energy consumed, the measurements are relatively consistent, but if delivered energy is also taken into consideration, the results could prove to be misleading and ambiguous [13,23]. Furthermore, both operating and embodied energies must be measured in their primary energy consumption terms in order to attain consistency and to acquire the most appropriate environmental implications in terms of CO<sub>2</sub> emissions [23]. Inclusion of delivered energy in embodied energy calculations creates complications while comparing energy values [35]. A better comparability in the energy database could be achieved if primary energy is used in the calculations [17]. Pears [49] asserts that if primary energy is considered instead of delivered energy, the embodied energy results could be 30–40 percent higher in building materials. Table 3 (source: Sartori and Hestnes [13]) shows research studies that have subjectively selected the type of energy to be included in their study.

### 5.5. Age of data sources

Age of data source has a significant impact on the comparability of the energy database, as old data are derived from an obsolete technology of manufacturing that is not as energy efficient as the new technology and thus, they differ in their values. Consideration of old transportation energy data could affect energy values, as new vehicles possess greater fuel efficiency and a different fuel structure. Any study based on such conflicting data sources could be misleading and uncertain [47,51]. Building material performance and material production efficiency will be enhanced over time and could be responsible for variations in measurement figures [25,32,38]. Hammond and Jones [55] considered modern data sources in establishing the inventory of carbon and energy, as they are more relevant, certain and possess temporal representativeness.

### 5.6. Source of data

Researchers adopt different approaches to data acquisition. Some derive their own embodied energy coefficient and others refer to an embodied energy database prepared by other researchers. This subjective choice influences the final results significantly [7,46]. Economic information sources like national input/output tables, energy tariffs and product cost, usually diverge and affect the analysis if based on the input/output method. Most published figures of embodied energy in building materials are derived using a single source of information that questions the accuracy and reliability of the data source [49]. Peereboom et al. [47] suggest that people practicing life cycle analysis (LCA) rely on various sources of information and do not have access to primary

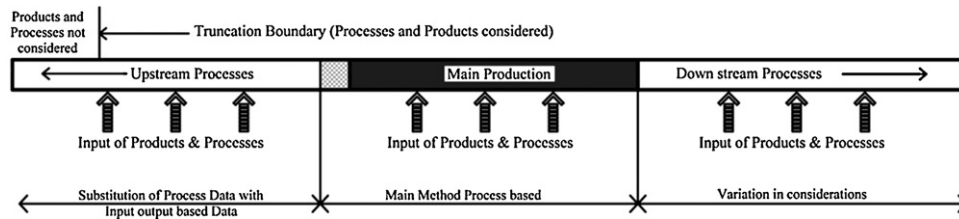


Fig. 7. Process-based hybrid analysis.

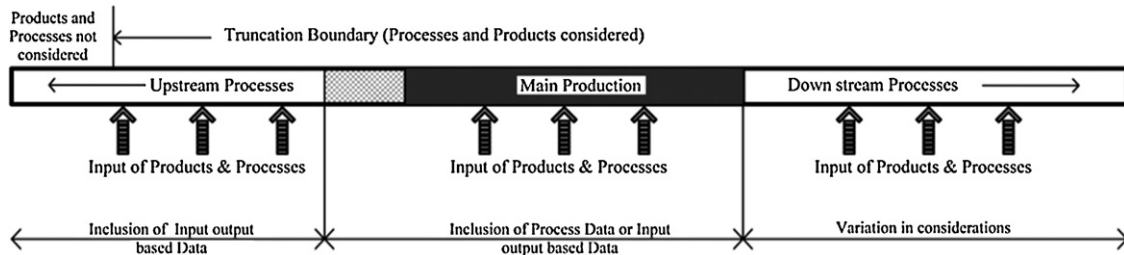


Fig. 8. Input-output-based hybrid analysis.

data resulting in uncertainty and variability in LCA results. Data source is an important parameter and its reliability, uncertainty and transparency must be considered while performing LCA [26,51].

5.7. Completeness of data

Menzies et al. [54] and Peereboom et al. [47] argue that researchers often do not have access to primary data sources and they rely on incomplete secondary data sources. Moreover, these referenced data sources are incomplete due to either an improper method of calculation or to the subjective selection of system boundaries. Menzies et al. [54] suggest that accessibility of data, methodology adopted, and selection of system boundaries govern the completeness of data that eventually affects the reliability of end results. According to Alcorn and Wood [51], completeness of data is a vital quality that should be considered while choosing one material dataset over another.

5.8. Technology of manufacturing processes

Manufacturing building materials using different technologies in the same time and at the same geographic location could reflect

dissimilar energy consumption. Use of differing production technology and type of energy used in the process could bring large differences to embodied energy figures [49]. Huijbregts et al. [59] point out the necessary technological correlation between the study and the data source, which is significant in LCA. ISO 14040 [53] states the need for technological representativeness of data while performing LCA of products. Technological representativeness is an important quality of data that should be taken into account in order to eliminate the inconsistency and variability of results [2,10,19,47,54].

5.9. Feedstock energy consideration

Feedstock energy is the energy used as an ingredient in the production process of a material. Petrochemicals like oil and gas are used as material input in the manufacturing process of products such as plastics and rubber. Feedstock energy is considered in the calculation of the total embodied energy of a material, if such valuable energy resources are used in manufacturing the materials [55]. Exclusion or inclusion of feedstock energy in embodied energy calculation or LCA could result in varying energy figures, and such figures are not comparable [38].

Table 3 Studies showing subjective selection of type of energy (Source: Sartori and Hestnes [13]).

Energy considerations in various embodied energy studies					
Source	Operating energy	Embodied energy	Recycling	Other energy	LCA
Adalberth et al. (2001)	End-use	I, T+f	✓	✓	✓
Adalberth (1997)	End-use	I, T+f		✓	
Adalberth (1999)	End-use	I, T+f	✓	✓	
Cole and Kernan (1996)	? Primary	I, T		✓	
Fay et al. [58]	Primary	I, T			
Feist (1996)	Primary	I, T			
Hallquist (1978)	? End-use	I		✓	
Hannon et al. [15]	? End-use	I		✓	
Mithraratne et al. (2004)	Primary	I, T			
Scheuer et al. (2003)	Primary	I, T+f		✓	
Suzuki and Oka (1998)	? Primary	I, T		✓	✓
Thormark (2002)	Primary	T+f	✓		
Treloar et al. (2000)	Primary	I, T			
Winther and Hestnes (1999)	End-use	T+f			
Winther (1998)	End-use	I, T+f	✓		
Zimmermann et al. (2005)	Primary	T			

I, initial; T, total; +f, feed stock energy included; ?, indicates no clear specification.

### 5.10. Temporal representativeness

Temporal correlation is a vital data quality indicator in embodied energy analysis and LCA [46,47,51,60]. Some energy studies are based on recently developed technologies, while some studies consider a mix of new and old technologies [61]. The end results of such studies differ and are not consistent.

Ding [7] states, by citing Kohler (1991), that a measurement figure is a function of what is included or excluded, thus it is difficult to reach a universally applicable database of measured values. Ding [7] observes that such deviations could be misleading and could distort the results of embodied energy analysis. Thus, it is very important to establish a set of guidelines or frameworks in order to monitor the measurement process. Furthermore, there is a need to accumulate all available data, then analyze and screen it against a template of criteria in order to establish a universally applicable and comparable database.

## 6. Summary

Building materials have the promising potential of significantly reducing energy use in the construction industry as EE is gaining importance among researchers, professionals, builders and material manufacturers. Current research efforts in the form of embodied energy inventories and methodologies suffer from inaccuracy and unreliability of energy data and thus are incomplete and inaccurate. This problem is due to parameters that vary and is related to various stages of embodied energy analysis. There is a stated and identified need to address the problem of variation and inconsistency by identifying and eliminating impacts of differing embodied energy parameters.

This paper identifies and presents a set of parameters that differ and which cause variation and inconsistency in embodied energy figures. This paper discusses the existing state of unclear interpretation about embodied energy and provides an idea about the inherent variation. The literature indicates that the geographic location is stated by most of the studies while feedstock energy consideration is the one least stated. These parameters, if addressed, could result in a consistent, translatable and comparable database of embodied energy of building materials.

This paper points out the need to evolve a standardized approach to data collection (embodied energy) that includes necessary guidelines and requirements to address difference of parameters, which could be followed by research and practice worldwide. Once the industry has a standard template for collecting and analyzing information, an energy economy that accounts for most of the energy embodied in a building will be useful to compare products and buildings regarding effective use of energy.

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