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Embodied energy assessment of building materials in India using process and input–output analysis

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ABSTRACT

Growing demand for urban built spaces has resulted in unprecedented exponential rise in production and consumption of building materials in construction. Production of materials requires significant energy and contributes to pollution and green house gas (GHG) emissions. Efforts aimed at reducing energy consumption and pollution involved with the production of materials fundamentally requires their quantification. Embodied energy (EE) of building materials comprises the total energy expenditure involved in the material production including all upstream processes such as raw material extraction and transportation. The current paper deals with EE of a few common building materials consumed in bulk in Indian construction industry. These values have been assessed based on actual industrial survey data. Current studies on EE of building materials lack agreement primarily with regard to method of assessment and energy supply assumptions (whether expressed in terms of end use energy or primary energy). The current paper examines the suitability of two basic methods; process analysis and input–output method and identifies process analysis as appropriate for EE assessment in the Indian context. A comparison of EE values of building materials in terms of the two energy supply assumptions has also been carried out to investigate the associated discrepancy. The results revealed significant difference in EE of materials whose production involves significant electrical energy expenditure relative to thermal energy use.

1. Introduction

Material consumption in construction industry makes up significant share of overall resource consumption in India. Annual consumption of construction materials in India is exceeding 2 billion tonnes. Further, energy expenditure for manufacture of building materials constitutes 20–25% of India's total energy demand [1]. Energy expenditure always results in detrimental emissions and pollution. Production and transport of building materials contribute to environmental impacts such as GHG (green house gas) emissions, global warming, pollution, resource depletion and loss of bio diversity. An estimated 30% of GHG emissions are contributed by the construction sector in India [1]. Cement and steel industries represent 7.5% and 6.8%, respectively, of net GHG emissions from India. Share of transportation sector is 8.22% of net GHG emissions from the country [2,3]. The above statistics reveal that buildings and related industries represent a significant potential for interventions to reduce GHG emissions through reduction of material and energy consumption. The identification of appropriate strategies and/or measures to reduce resource and energy consumption in buildings primarily requires proper estimation/measurement in current use. Embodied energy (EE) of building materials constitutes the total energy expenditure for manufacture of building materials including that for raw material extraction and associated transportation. EE assessment of building materials reveals the extent of energy consumed and associated GHG emissions in their manufacture.

There have been extensive efforts in last few decades towards assessment of EE for a wide variety of building materials. Most studies lack consensus on the assessment method and a comprehensive assessment framework. Further, the EE values from various studies differ widely consequent to the differences in study area, energy assessment in terms of primary and end use energy, industrial characteristics such as raw material procurement, production technology and data characteristics. This emphasizes the need for region specific database for EE assessment of building materials. This paper compiles EE values for a few common building

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materials consumed in bulk in Indian construction industry, provides EE values estimates adopting two basic methods and for two energy supply assumptions (primary energy or end use energy). Primary energy conversion factors derived for various fuel sources have been found to be three times the value derived from end-use energy. Also, the study highlights the problems associated with the use of input–output analysis for estimation of EE of construction materials in the Indian context.

2. Earlier investigations

Studies on embodied energy of building materials primarily pertains to various methods of assessment, compilation of EE values of various materials and investigations with regard to factors affecting EE assessment. Several studies [4,5] showed that it is possible to capture the EE of materials through process analysis, input–output (I/O) analysis and hybrid analysis, process analysis being more realistic with regard to main process energy omitting the remote upstream and downstream processes while I/O analysis presents a comprehensive framework including all the upstream and downstream processes with less clarity on main process energy. Existing compilation on embodied energy (EE) values for building materials include mainly open-access institutional, industrial, commercial and individual databases [4]. There are only few distinct individual studies on embodied energy assessment of common building materials. A few studies investigated the causes for wide variations in available EE values. Table 1 summarizes the characteristics of various studies pertaining to EE in building materials.

Literature review reveals discrepancies in EE assessment with regard to the method of assessment, the system boundary definitions, discrepancy in terms of end use energy and primary energy, industrial processes and data characteristics. Further, process analysis is recommended for product specific energy analysis, since the main manufacturing process represents the major contribution to

Table 1
Summary of literature review.

Sl. no.	Year	Type of study	Authors [reference]	Salient remarks
1	1995	Methods of assessment	Lave et al. [6]	Suggests I/O method for LCA studies
2	1996	Methods of assessment and factors affecting EE values	Pullen [7]	Suggests process analysis for specific materials. Data quality and error in estimation affects EE values
3	1997	Methods of assessment and compilation of EE values	Baird et al. [8]	Compilation of EE data from 1983–1996 for construction materials in New Zealand. Recommends hybrid analysis for EE assessment
4	2000	Methods of assessment	Lenzen M. [9]	Highlights suitability of process analysis for product specific EE assessment
5	2001	Methods of assessment	Treloar G. J. et al. [10]	Presents a hybrid analysis for EE assessment
6	2004	Methods of assessment	Crawford R. H. and Treloar G. J. [5]	Observe higher EE values for buildings using a proposed I/O based hybrid method when compared to conventional methods
7	2004	Methods of assessment	Emmanuel R. [11]	Recommends process analysis for building materials
8	2007	Methods of assessment	Nassen J. et al. [12]	Observe significant difference in EE of buildings based on process analysis and I/O method but less difference in EE of building materials based on the same methods
9	2008	Methods of assessment and factors affecting EE values	Hammond G. P. and Jones C. I. [13]	Recommends process analysis for industry specific direct energy data and input–output method for more accurate data on indirect energy requirements. Discrepancy in boundary conditions and the age of data sources cause variation in EE values
10	2007	Methods of assessment and factors affecting EE values	Menzies et al. [4]	Recommends I/O method for policy decisions and process analysis for comparing various industry specific products options. Reliability and quality of various databases, system boundary, assumptions on energy sources and supply, product specification, manufacturing process and data characteristics like age, geographic location, transparency and error cause variation in EE values
11	2008	Compilation of EE values	University of Bath, UK [14]	Inventory for Carbon and Energy (ICE)
12	2003	Compilation of EE values	Centre for Building Performance Research, New Zealand (NZ) [15]	Open database of EE values
13	2012	Compilation of EE values	National Renewable Energy Laboratory (NREL) [16]	United States Life Cycle Inventory database
14	2012	Compilation of EE values	ATHENA Sustainable Materials Institute, Canada [17]	ASMI building material inventory
15	1994	Compilation of EE values and factors affecting EE values	Buchanan A. H. and Honey B. G. [18]	Database of EE of materials for New Zealand. Difference in raw materials, Industry processes, process efficiency, energy usage and economy of the country affect EE values
16	1997	Compilation of EE values	Adalberth K. [19]	EE values for building materials based on prefabricated wood-framework single-unit dwellings in Sweden
17	2003	Compilation of EE values	Reddy B. V. V. and Jagadish K. S. [20]	EE of few building materials in India using process analysis
18	2004	Compilation of EE values	Dias W. P. S. and Pooliyadda S. P. [21]	EE values for Sri Lankan building materials using process analysis
19	2008	Compilation of EE values	Langston Y. L. and Langston C. A. [22]	EE values using Australian data using I/O method
20	2009	Compilation of EE values	Kofoworola O. F. and Gheewala S. H. [23]	EE values for building materials in Thailand using I/O method
21	1992	Factors affecting EE values	Cole R. J. and Rousseau D. [24]	Illustrates the importance of system boundary definition
22	1996	Factors affecting EE values	Pears [25]	Policy guidelines in EE considerations
23	2000	Factors affecting EE values	Lenzen M. and Dey C. [26]	Truncation error in EE assessment
24	2010	Factors affecting EE values	Dixit M. K. et al. [27]	System boundaries, methods of energy analysis, geographic location of study area, primary and delivered energy, age of data sources, source of data, completeness of data, technology of manufacturing process, feedstock energy consideration and temporal representativeness

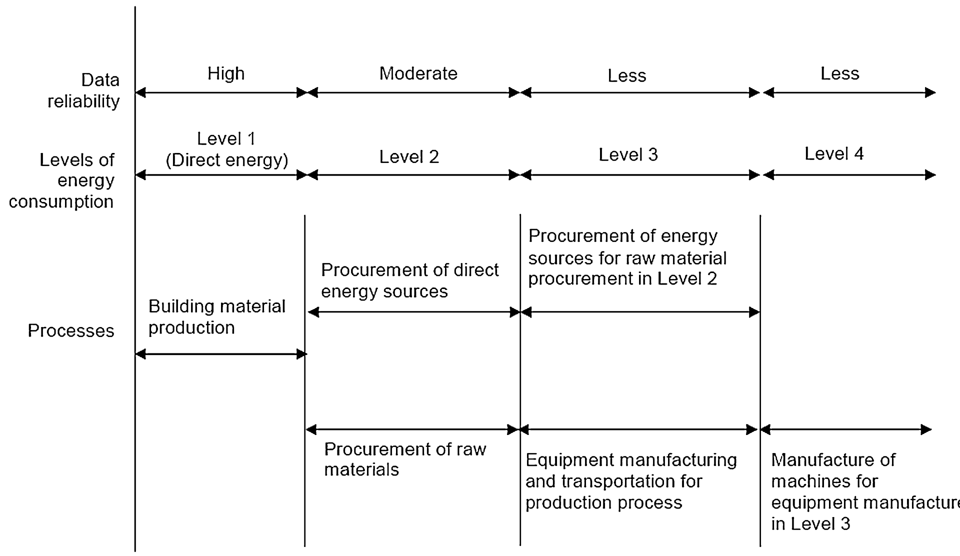

Fig. 1. Generic illustration for four level system boundary for EE assessment.

the embodied energy of the material. However, a simplified framework would be more convenient for process based data collection and energy assessment.

3. Objective and scope of current study

Scope of the present study included assessing the EE of few common building materials in Indian industry using a process analysis based framework and demonstrating unsuitability of I/O method of EE assessment for the materials in the Indian context. Based on system boundary definition suggested in International Federation of Institute for Advanced Study (IFIAS) workshop [21], a process analysis based framework was developed for EE assessment. The differences in the EE values occurring due to the type of energy source (primary or end use) are also dealt with. Based on I/O transaction tables, EE of various materials was assessed and analyzed.

4. Process analysis based EE assessment

The earliest attempt to comprehend various processes involved in estimating the EE value of a material was suggested in International Federation of Institute for Advanced Study (IFIAS) workshop (1974) [21]. The above methodology identifies four levels or system boundaries associated with the manufacture of various building materials, as illustrated in Fig. 1. The first level includes the direct energy consumption in the production process. Level 2 represents the energy consumed in extraction of raw materials, its transportation and procurement of energy sources for level 1. Level 3 includes energy spent for manufacturing equipments and its transportation for the process in level 1 and also for procuring energy sources for raw materials procurement in level 2. Level 4 mainly includes the direct energy spent in making machines which support the manufacture of equipments required for the process in level 1.

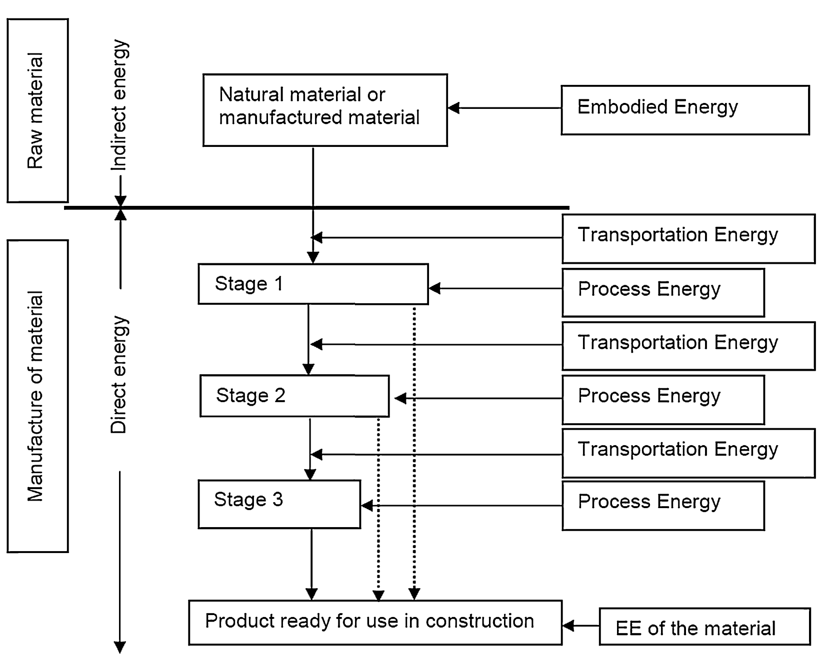

Fig. 2. EE assessment framework adopted in the present study.

Table 2
List of materials included in the present study.

Basic materials	Building products
Sand	Burnt clay brick
Coarse aggregate	Concrete block
Cement	Laterite block
Steel	Ceramic tile
Glass	Clay roofing tile
Aluminium	Polished granite slabs
	Polished marble slabs

Energy spent in levels 1 and 2 represents a major share of the embodied energy of the material. The first two levels contribute more than 90% of the total energy consumption. Also, reliable assessment of the energy consumed in levels 3 and 4 is difficult [4,8,21]. Hence, from a practical point of view, keeping in mind feasibility in data collection and analysis, a framework has been proposed building on the first two levels of IFIAS definition for system boundary for EE assessment as illustrated in Fig. 2.

The embodied energy of any material has a direct component and an indirect component. The major indirect component represents the energy for extraction and transportation of raw materials for the building material under consideration. The raw materials could be natural materials, manufactured products, industrial waste byproducts, recycled materials or reused materials. If the raw material is a natural material, then the indirect component is the energy spent in extracting the material. If it is a manufactured material, the indirect component represents the embodied energy of the material which includes energy consumption for the manufacturing process and associated raw material procurement. If the raw material is any industrial waste product or a reused material, the indirect energy component could be considered zero. If it is a recycled material, the indirect energy represents the energy for recycling. The direct energy component reflects the energy spent in actual production processes. It could be the energy in more than one process and transportation energy depending on the stages of processing it undergoes.

EE of commonly used building materials consumed in bulk quantities in India has been assessed. These materials can be grouped into two categories such as basic materials and building products. Table 2 gives the list of materials for which EE assessment was studied. Details of EE assessment and the EE values of these materials are discussed in the following sections

4.1. Embodied energy of basic materials

Basic materials considered include cement, steel, glass, aluminium and aggregates (fine and coarse).

The EE of Ordinary Portland Cement (OPC) was determined for two different cement industries. Table 3 gives a summary of energy consumption details in these industries. Fig. 3 illustrates adoption of general framework for EE assessment of cement. The EE values of cement are 3.72 MJ/kg and 2.38 MJ/kg for Industry 1 and 2, respectively. To illustrate the methodology, EE of cement was estimated as the sum of the indirect energy component and the direct energy component. Indirect energy component, in this case, mainly represents the energy for extraction of lime stone. Direct energy constitutes energy for transportation of lime stone and other raw materials to the industries and the process energy which includes the energy spent for the four processes.

EE of steel was estimated for a steel plant of capacity of 4.2×10^6 t of saleable steel per annum. The EE of steel products is 32.24 MJ/kg as illustrated in Table 3. Thermal energy forms nearly 97% of EE. Direct energy expended for the main processes represented about 92.5% of total EE.

Table 3
Summary of EE assessment in building materials.

Sl. no.	Energy component (MJ/kg)	Basic materials						Building products						
		Cement		Steel	Glass	Aluminium cold rolled coils	Aggregates	Solid concrete block		Laterite block	Ceramic tiles	Polished granite slab	Polished marble slab	Mangalore pattern clay roofing tile
		Industry 1	Industry 2					Industry 1	Industry 2					
1	Indirect energy													
1a	Raw material extraction/embodied energy	0.2	0	0.08	0.02	0.15	0.02	0.14	0.204	–	–	–	–	–
2	Direct energy													
2a	Raw material transportation	0	0	0.04	0.16	–	0.01	0.018	0.022		0.13	0.102	1.52	
2b	Process energy	3.5	2	32.12	7.7	141.4	0.01	0.019	0.017	0.0069	10.5	0.003	0.001	4.93
3	Embodied energy (MJ/kg)	3.7	2	32.24	7.88	141.55	0.04	0.177	0.243	0.0069	10.63	0.105	1.521	4.93

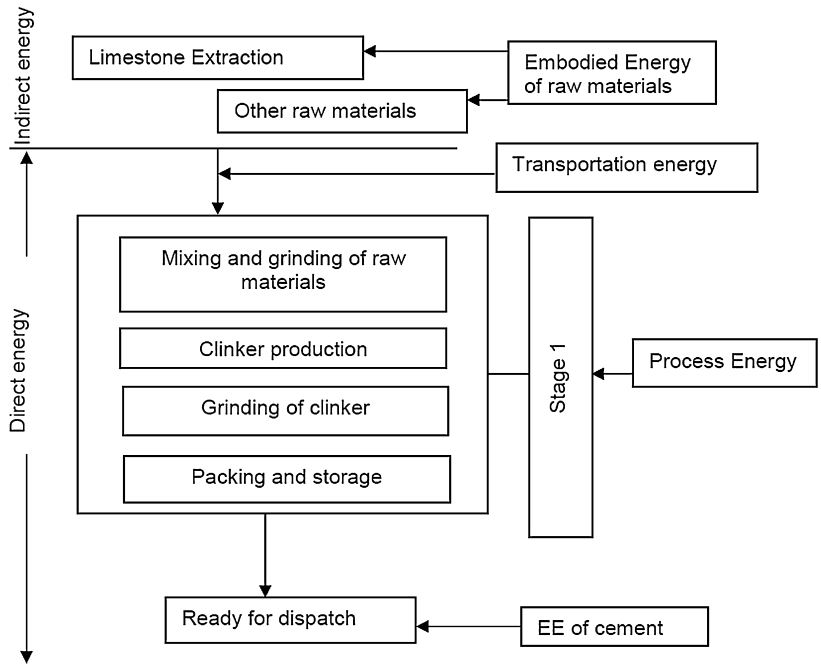

Fig. 3. Framework adopted for EE assessment of cement.

EE of glass was estimated using the data obtained from a float glass manufacturing plant. The production process involves raw material batch preparation, melting of batch in a furnace, float process (floating of molten glass on bath of molten tin), annealing, inspection and storage. EE of float glass was estimated at 7.88 MJ/kg as illustrated in Table 3. The main process represents about 98% of EE of float glass.

EE of aluminium cold rolled coils was estimated using the data from an aluminium rolling mill where primary aluminium is rolled into coils and supplied as raw material for different industries. Energy data for bauxite mining, production of alumina and primary aluminium have been derived from industry research reports and annual reports [28–30]. Fig. 4 provides the framework adopted for assessment of EE of aluminium cold rolled coils. EE of aluminium cold rolled coils is 141.55 MJ/kg as illustrated in Table 3. Thermal and electrical energy represent 70.66% and 29.33% of total EE, respectively. EE of aluminium composite panels (ACPs) was also estimated using the data from an ACP manufacturing unit. Embodied energy of an aluminium composite panels was estimated at 549.16 MJ/m^2.

Energy consumption in the various processes involved in production of coarse aggregate and manufactured sand was collected through a survey of an industry producing both coarse and fine aggregates. The EE of manufactured sand and coarse aggregates is

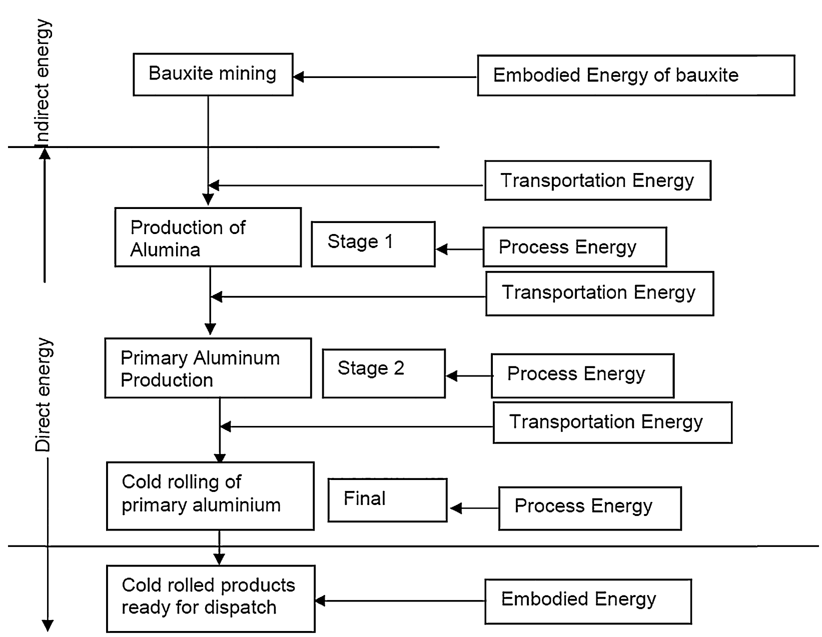

Fig. 4. Framework adopted for EE assessment of aluminium rolled coils.

Table 4
EE values estimated for burnt clay bricks.

Sl. no.	Type of kiln	Type of fuel	Type of brick	Embodied energy (MJ/kg)		
				Electrical	Thermal	Total
1	BTK	Electricity and firewood	Table moulded	0.12	1.15	1.27
2	BTK	Electricity and firewood	Wirecut	0.003	2.485	2.5
3	BTK	Electricity and firewood	Wirecut	0.08	2.88	2.96
4	BTK	Electricity and firewood	Wirecut	0.044	4.006	4.05
5	Clamp	Firewood	Country brick	0	2.9	2.9
6	Clamp	Firewood	Country brick	0	1.67	1.67
7	BTK	Firewood, coal and diesel	Table moulded	0	2.22	2.22
8	Down-draught	Biomass	Table moulded	0	3.36	3.36
9	Down-draught	Firewood	Table moulded	0	3.48	3.48
10	Hoffmann	Firewood and diesel	Table moulded	0	2.94	2.94
11	BTK	Coal	Table moulded	0	1.99	1.99
12	VSBK	Electricity and coal	Table moulded	0.001	1.199	1.20
13	Down-draught	Coal	Table moulded	0	1.88	1.88
14	Improved BTK	Electricity and coal	Table moulded	0.01	1.5	1.51

0.037 MJ/kg as illustrated in Table 3. The study reveals that EE for the crushed aggregates is lower than the energy spent for transportation over a distance of 100 km.

4.2. Building products

Table 4 provides EE values estimated from 14 case studies with details of the brick industries such as type of kiln, fuel type and type of brick (Table moulded or wire cut). EE assessment of a few case studies is illustrated in Table 5. In majority of the case studies, the indirect energy component i.e., the energy expenditure for extraction of soil (EE of soil) was negligible since manual labour has been used for extraction. For production of bricks in clamps, the energy consumption for soil transportation is nil since the clamps are generally located close to the soil source. For other types of kilns, some amount of energy is spent for transportation of soil from its place of extraction to the industry, which is accounted as raw material transportation energy in the present study. Process energy represented more than 96% of EE for most of the industries. Energy expenditure for firing the green bricks represents the highest contribution to the process energy. The results given in Table 4 indicate highest energy consumption for wire cut bricks (4.05 MJ/kg) in a BTK and the lowest for Table moulded brick in VSBK kiln (1.2 MJ/kg). The EE of bricks is in the range of 1.2–4.05 MJ/kg with an average value of 2.42 MJ/kg for different types of kilns in the country. Fig. 5 shows a radar diagram comparing the EE values for bricks from present study and literature data [31]. The range of EE for burnt clay bricks from literature is 1.7–3.00 MJ/kg (see Table 6).

Two concrete block making units were surveyed, designated as Unit I and Unit II. Unit I produced only solid concrete blocks whereas Unit II produced both solid and hollow concrete blocks. The cement content used in these two units is in the range of 4.5–9%. Block production in these Units uses concrete mixes adopting very low cement content.

Table 3 summarizes the embodied energy estimates for concrete blocks based on the study. The EE for concrete blocks is in the range

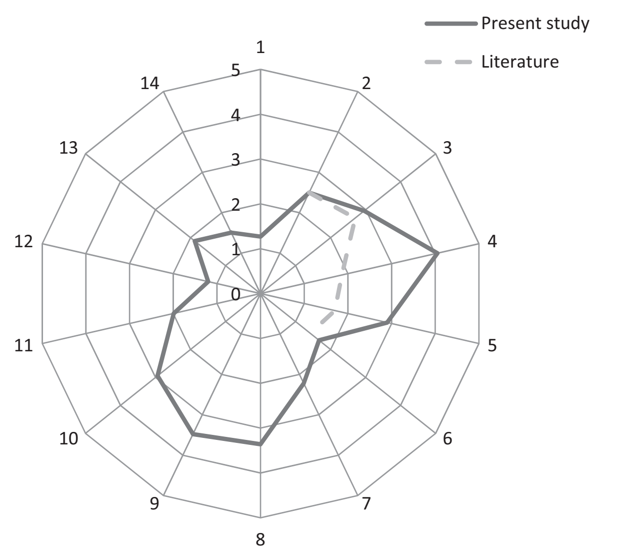

Fig. 5. Comparison of EE of burnt clay bricks from present study and literature.

of 0.17–0.25 MJ/kg. This range is much lower than the values of 0.67–0.9 MJ/kg reported in literature (see Table 6). This could be attributed to the higher percentage of cement content or addition of aggregate extraction energy for estimation.

Laterite blocks are solid blocks extracted or quarried from the laterite soil zones. Blocks cut from such deposits are used as masonry units in building construction [32]. The commonly available sizes include 290 × 140 × 240 mm, 350 × 200 × 200 mm and 400 × 200 × 250 mm. Generally, laterite blocks are extracted manually or adopting a semi-mechanized technique. The present study estimated EE of laterite blocks from a laterite quarry where a diesel operated cutting machine is used for extraction of blocks. Since there is zero processing energy for laterite blocks, the embodied energy of the block (400 × 200 × 250 mm) (see Table 3) is the

Table 5
Embodied energy of burnt clay bricks for a few case studies.

Sl. no.	Processes	Energy (MJ/kg)				
	Type of kiln	Clamp	BTK	Down-draught	Hoffmann	VSBK
1	Indirect energy component					
1a	Extraction of raw materials	0	0	0	0	0
2	Direct energy components					
2a	Raw material transportation	0	0.044	0.022	0.023	0.045
2b	Process energy	2.9	2.18	3.46	2.92	1.16
3	Embodied energy of burnt clay brick (MJ/kg)	2.9	2.22	3.48	2.94	1.2

Table 6
EE of building materials–present study versus literature data.

Sl. no.	Building materials	EE in MJ/kg		
		Present study		Values from literature [14,18,20]
		For 1 kW h = 3.6 MJ*	For 1 kW h = 11.22 MJ**	
1	Cement	2.38 and 3.72	2.91 and 4.32	3.60–9.29
2	Steel	32.24	34.23	20.62–42.00
3	Glass	7.88	8.94	6.80–31.50
4	Aluminium rolled coil	141.55	150.69	130.0–236.80
5	Manufactured sand	0.037	0.062	0.10–1.14
6	Clay roofing tile	4.93	5.08	6.50
7	Burnt clay bricks	1.2–4.05	1.2–4.14	1.70–3.00
8	Solid concrete blocks	0.17–0.25	0.23–0.35	0.67–0.90
9	Laterite stone blocks	0.007	0.007	Not available
10	Ceramic tiles	10.63	18.00	2.20–14.87
11	Polished granite stone slab	0.105	0.111	0.01–13.90
12	Polished marble stone slab	1.53	1.53	2.00

* In terms of end use energy.
** In terms of primary energy.

energy spent for extraction of blocks which is 0.25 MJ/block or 0.0069 MJ/kg. Laterite block is a natural material produced and used locally without much transportation, and hence, EE of laterite block is very low.

In the present study, EE of ceramic tiles was estimated through a survey of a local industry with a production capacity of 52650 tonnes per year. EE value of ceramic tile was estimated and has a value of 10.63 MJ/kg as illustrated in Table 3. Thermal energy and electrical energy form 67% and 33% of total EE, respectively.

A granite and marble stone processing unit was examined for energy consumption details. The processing unit procures granite blocks from an average distance of 100 km and marble stone blocks from an average distance of 1500 km. EE of polished granite and marble stone slabs were estimated at 0.105 MJ/kg and 1.53 MJ/kg, respectively, as illustrated in Table 3. With regard to granite and marble processing, it was observed that transportation energy represents nearly 97% and 99.9% of the embodied energy of granite and marble stone slabs, respectively. Hence, local use of such materials, avoiding long distance hauling would make them more energy efficient

Burnt clay roofing tiles generally referred to as Mangalore tiles are made from clay and are used for roofing in the southern peninsular region of India. Generally, the tiles are available in 420 × 250 mm size weighing around 2.5 kg/tile. These tiles are commonly used for roofing systems of low-rise buildings. Data for Mangalore tile manufacturing was obtained by surveying an industry with an annual production of about 100,000 tiles. The industry uses Hoffmann's continuous kiln for firing the tiles. Fuels used include firewood and electricity. Firewood is used for firing operations and electricity is used in processes such as raw material mixing and tile moulding. The indirect energy component was negligible for the case study since clay extracted locally was the main raw material. Table 3 gives EE details for the tiles. EE of the roofing tiles is 4.93 MJ/kg. Electrical energy is about 1.5% of total EE of the tile.

5. Comparison of embodied energy values from different energy sources

In EE estimation, two types of energy conversion factors are possible based on either end use energy or primary energy. The conversion factor is 1 kW h = 3.6 MJ when end use energy is considered and in the Indian context 1 kW h = 11.22 MJ when primary energy is considered. Few studies [4,25,27] highlight the importance of presenting EE of materials in terms of primary energy. EE assessment in terms of primary energy takes into account the method of generation of electricity and distribution losses etc. The factor of 11.22 accounts for the fuel mix for electricity generation in India which comprises 68% thermal power, 17% hydropower, 2% nuclear power and 12% renewable power [33] and also 27% transmission losses [34]. This factor representing the primary energy is more than three times the value obtained from end use energy consideration. Table 6 gives a comparison of EE values of buildings assessed adopting both the conversion factors and EE values from literature. Use of conversion factor (11.22) based on primary energy results in 2–6.5% increase in EE of materials such as steel, aluminium, burnt clay bricks, polished granite slab and clay roofing tiles. For materials such as glass and cement the increase is 13–22.5% and for materials such as aggregates and ceramic tiles there is 30–70% increase. For polished marble stone slab, use of the conversion factor does not change the EE value since electrical energy forms only 0.1% of total EE. Comparison of EE values of different building materials considering variation in energy source and the EE values from literature reveals that EE values vary widely, time dependent due to changes in processes and efficiency, and it is impossible to arrive at a single unique value for EE of any material.

6. Embodied energy assessment using input–output (I/O) method

Method adopted for assessment of EE of a material is one of the significant factors affecting the accuracy of EE value derived. Several studies [4,5] show that it is possible to capture the EE of materials through process analysis, I/O analysis and hybrid analysis. Existing studies recommend process method for material or product specific EE assessment. I/O method using input–output transaction tables (IOTT) involves various assumptions which render it unreliable for embodied energy calculations for specific products among construction materials. The current investigation attempted to assess EE of specific materials using I/O analysis and compare with the values obtained from the process analysis frame work in the Indian context.

6.1. Indian input–output transaction tables (IOTT)

The first input–output transaction tables jointly prepared by Central Statistical Organization (CSO) and Planning Commission for the year 1968–69 were published in National Accounts Statistics in 1978. The latest I/O Tables [35] available are for the year 2003–2004 and re-published in 2008. The present Indian IOTT have 130 sector. Indian IOTT have 68 sectors grouped under the 'manufacturing'

Table 7
EE values for materials using I/O method and literature data.

Sl. no.	I/O method		Type of material	Literature data [14,18,20] (MJ/kg)
	Type of industry	EE (MJ/kg)		
1	Wood and wood products	7.00–34.10	Wood	4.60–15.00
2	Rubber products	41.90–51.60	Rubber	67.50–140.00
3	Paints, varnishes and lacquers	13.50–194.00	Paints	60.20–90.40
4	Structural clay products	0.75–3.00	Burnt clay bricks	1.42–6.50
5	Cement	4.67–8.05	Cement	3.60–9.29
6	Iron and steel foundries	55.29–60.05	Structural Steel	20.62–42.00

sector and include the following construction materials production related sectors.

1. Furniture and fixtures—wooden (Sector 55)
2. Wood and wood products (Sector 56)
3. Rubber products (Sector 61)
4. Plastic products (Sector 62)
5. Paints, varnishes and lacquers (Sector 69)
6. Structural clay products (Sector 74)
7. Cement (Sector 75)
8. Iron, steel and ferro alloys (Sector 77)
9. Iron and steel casting, and forging (Sector 78)
10. Iron and steel foundries (Sector 79)
11. Non ferrous basic metals (Sector 80)
12. Electrical wires and cables (Sector 89).

The following building material industries that have outputs to the construction sector (sector 106) were considered for embodied energy assessment.

- Wood and wood products (Sector 56)
- Rubber products (Sector 61)
- Paints, varnishes and lacquers (Sector 69)
- Structural clay products (Sector 74)
- Cement (Sector 75)
- Iron and steel foundries (Sector 79).

The present study observed lack of clarity with regard to monetary flows between various industries in the IOTT. For example, for each commodity (in columns) there is monetary flow associated with outputs from different industries (in rows). For example, for the cement industry, there is input (in monetary unit) flow from the following industries:

1. Paints, varnishes and lacquers
2. Other chemicals
3. Structural clay products
4. Cement
5. Other non metallic mineral products
6. Iron, steel and ferroalloys
7. Electrical appliances.

To obtain the actual production of cement, it would not be appropriate to consider the total monetary flow from all the industries and convert the same in terms of bags of cement or kg of cement since the critical production is only from the cement industry. Hence, there exists an uncertainty regarding the monetary flow to be considered for estimation of actual production of this commodity. For the present study, the total monetary value from the particular industry was considered as an estimate of the actual production of these commodities.

Also, there is lack of clarity regarding the details or components of monetary flows associated with various inputs and outputs. For any building material, the total monetary outflow from all the industries (including the related industry) should be either equal to or more than the input monetary flow to the construction industry. For cement the monetary value of total output from all industries is given to be less than the monetary inflow to the construction industry. Also, for structural clay products, the monetary value of output from the particular industry is less than that of the input to the construction industry. These factors pose problems for EE assessment of materials using the IOTT.

Table 7 summarizes the embodied energy values for the products estimated using I/O method and provides a comparison with literature data. In the Table, literature data represents EE values for specific materials such as wood, rubber, paints, burnt clay bricks, cement and steel unlike the EE values based on I/O method which represent the EE for group of products.

For the sectors such as wood and wood products, rubber products, structural clay products, steel etc. the output constitutes more than one product. Hence, embodied energy of a particular product (building material) such as burnt clay brick, clay tile, types of paints, reinforcement steel etc. cannot be assessed as it is impossible to extract energy consumption data for individual products from the available aggregated data. Also, the analysis shows that for a group of products from a single sector, the assumption of a single price value is incorrect as the cost is different for each product from the same sector. For example, the products from the sector 'structural clay products' might include clay bricks, hollow clay blocks, clay roofing tiles, clay paver tiles etc. which vary significantly with regard to their prices. Also, lack of product specific data on prices and quantities of production makes EE assessment of the material difficult. Further, the IOTT do not include data for building materials like aggregates, concrete blocks, other masonry units and concrete products. Hence, the IOTT are less useful for estimating energy intensities of various other building materials.

Another factor which questions the suitability of I/O method for energy analysis is the tariff for different energy sources and commodities. Energy tariff varies widely across the country depending on the location of power generation, source of electricity, distribution losses etc. Also, the energy prices change quite frequently. Energy tariff is different for different groups of consumers like industries, domestic etc. A range of EE values was obtained for these groups of products corresponding to different product tariffs.

Thus, apart from the major disadvantages of I/O method such as various assumptions, unreliable data, lack of product specific data, high variability of energy and commodity tariffs etc., the following reasons render the method unsuitable for EE assessment in the Indian context.

- Lack of recent data as the existing Indian IOTT is 10 years old.
- Impossible to extract data on product specific energy consumption and quantity of production from the aggregate data for industries producing more than one commodity (e.g. Wood products, clay products, iron and steel foundries).
- I/O Tables do not cater to all the building products. No data available for EE assessment of aggregates, other masonry units like

concrete and stone blocks, stone slabs, float glass, ceramic products etc.
- IOTT indicates monetary outflow from various industries other than the related industry with regard to production of a commodity resulting in less clarity on monetary outflow related to actual production of the materials.
- Differences in energy tariffs and commodity tariffs across the country.
- Frequent changes in energy and commodity tariffs with time.
- Production of building materials such as burnt clay bricks, roofing tiles, concrete blocks, etc. in the unorganized sector.

The above disadvantages or limitations do not exist for process based EE assessment since the data pertains to a specific industry and its products. Hence, process based analysis is observed to be more appropriate for embodied energy assessment of building materials particularly for the Indian construction industry.

7. Conclusions

The current paper deals in depth with EE from a building materials life cycle perspective, and identifies various methodologies for their quantification. EE assessment can be carried out using process analysis, I/O analysis and hybrid analysis. I/O method of analysis is supposed to encompass the energy spent in upstream/downstream activities. Several assumptions underlie I/O method adopted for EE analysis. Detailed investigations on Indian input–output transaction tables have found them unviable for EE assessment of building materials in the Indian context. Unreliable data, lack of product specific data, high variability of energy and commodity tariffs across the country and out-of-date I/O Tables on time represent salient drawbacks associated with I/O method. The IOTT Tables for India are more than a decade old and also, it is difficult to access authentic I/O data Tables in many countries. These reasons render the I/O method unsuitable for EE assessment in the Indian context. A new process analysis based framework was eventually adopted for EE assessment study.

Among the basic materials considered, aluminium coils have highest EE value followed by steel, glass and cement. Among the masonry units considered, burnt clay bricks have high EE (1.2–4.05 MJ/kg) followed by concrete blocks (0.17–0.25 MJ/kg) and laterite stone blocks (0.007 MJ/kg). EE of concrete blocks is sensitive to the cement content used in the block manufacture. Process energy represents a significant contribution to EE for burnt clay bricks while raw material energy forms the major contribution to EE for concrete blocks.

EE of aggregates is very low at 0.04 MJ/kg, whereas ceramic floor tile has a high EE value at 10.63 MJ/kg. The polishing operations used in the production of granite and marble stone slabs do not contribute much to EE, whereas the transportation energy represents more than 95% of EE of polished stone slabs.

Generally, manufacturing of construction materials involves use of both electrical energy and thermal energy. The conversion factors that need to be applied differ and depend on use of either end use energy or primary energy. Use of higher conversion factor (based on primary energy) for converting electrical to thermal energy results in a magnified EE value depending upon the share of electrical and thermal energy use in the manufacturing process.

Comparison of EE values of different building materials considering variation in energy source and the EE values from literature reveals that EE values vary widely and are time dependent due to changes in processes and efficiency. It is most impracticable to arrive at a single unique value for EE of any building material. Therefore, EE estimate of a material at best can be represented as a range.

Thus, the current study provides EE values for a few common building materials and thereby serves as a methodology and database to support future studies and reporting on EE for building materials in India.

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