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Research Article

Embodied energy and operational energy computations for a typical G+3 residential building in Vijayawada city of Andhra Pradesh, India

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Abstract
Energy computations in commercial and residential buildings have been studied over the past few years by various researchers. The studies have revealed an interesting relation between the materials used in the building, the manufacturing process, the construction process, and its overall impact on the environment. However, limited studies have been conducted on the computation of the Embodied Energy (EE) and the Operational Energy (OE) of residential buildings. In the present investigation, an attempt has been made to compute these two factors (EE and OE) for a residential building situated in Vijayawada, Andhra Pradesh, India. The case study chosen here is an exciting example of a reinforced cement concrete framed structure with ground + three floors. Based on the conducted studies, the EE computations show that a huge amount of energy is used for materials such as cement, steel, and bricks. The use of alternative building materials to these and technologies can help in reducing EE. OE can be reduced during the lifetime of the building by implementing different methods of energy conservation. The energy consumption in a typical residential building depends on the types of appliances, usage hours, the consumption of the devices, etc. Changes in any one of these could alter the annual energy consumption, and thus, the OE. The EE content is experienced once separately from maintenance and renovation, whereas OE gathers over time and can be prejudiced throughout the life of the structure.

Keywords
Residential buildings, OE, Energy computations, EE, Thermal comfort.

1.Introduction
As the building industry takes up a significant part in the energy utilization of a country, builders and engineers are searching for better approaches to limit the energy utilization in buildings in order to prevent environmental pollution [1, 2]. The Operational Energy (OE) of buildings alone corresponds to 30–40% of the complete power consumption globally [3]. The building sector may be looked at while the motorist that is prominent of use and greenhouse gasoline emissions if embodied requirements. Hence, Embodied Energy (EE) and OE linked to building materials and transport requirements linked to the transportation to build people tend to be taken into consideration [4].

Among these reasons, decreasing the power usage and greenhouse gas emissions throughout the lifespan of the buildings is the focus of numerous studies.

However, predicated on the significant reviews related to the topic, most of the current research studies have been found to only quantify the operational and embodied power, omitting the transport demands [5]. The evaluations are tied to these two factors of the building when it comes to the working energy, and the embodied energy computation is ignored. Limiting the energy demand and controlling environmental pollution has a huge effect on climate change [6]. In addition, the contribution of the construction sector is significant to these factors [7], and optimumstrategies are required to control these factors. The energy consumed by buildings or other structures is significant because of their massiveness and life compared to other energy consumers such as

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machinery, automobiles, etc. [8, 9]. Computation of the life cycle energy and embodied energy is significant because every building component is built using high-energy materials such as steel, cement, burnt bricks, concrete and its products, etc. [10, 11]. The use of these materials has increased considerably, and a huge amount of energy is consumed during their manufacturing and transportation [12]. There is a need to quantify the energy involved in construction, i.e., the EE and the OE, so that their depreciation can be implemented in further works as well as in the usage of materials [13, 14]. Increased use of construction materials leads to carbon emissions, which contribute to global warming [15–18]. Construction materials such as cement, aluminum, glass, concrete, etc., contribute to approximately 10% of the total CO_2 in the environment [19–22]. The objectives of the present study are as follows:

- Computation of EE of the building components
- Analysis of OE during the usage of building.
- Measures for reducing the energy consumption and the overall EE and OE for the building.

The building industry is a predominant consumer of energy and a large carbon emitter. Thus, EE and OE are the two vital parameters that have a significant role in managing the adverse impact of the building industry on the environment [23]. Very few scientific studies have focused on assessing the energy consumed during the lifespan of a building and the cost repercussions of numerous energy reduction methods over the different machines associated with the built environment, especially in the Asian subcontinent. With the increasing population in the continent, the demand for dwellings has also increased; thus, directly impacting the demand for building materials. To successfully reduce the energy consumed in the built environment, it is critical to ensure that the solutions are efficient from the financial point of view and technically feasible [24]. The research that quantifies the lifespan, which balances the benefits and value requirements of various energy reduction steps, emphasizes the embodied, useful, and specific transport power when providing the solution for the life of the building [25, 26]. This could identify the essential affordable steps that give the maximum energy cost savings and can offer insights that could lead to unprecedented levels of decreased overall energy usage in domestic buildings. This paper focuses on EE and OE studies for a typical mid-rise residential building that is very common in urban scenarios and occupies a significant chunk of houses in urban areas in India. The scope of the investigation is restricted to the computation of EE of a residential building comprising of a Reinforced Cement Concrete (RCC) framed structure located in Vijayawada city, Andhra Pradesh, India. The following components have been considered in these computations:

- Isolated foundation inclusive of Plain Cement Concrete (PCC) bed
- Plinth beam
- Columns, beams, slabs
- Concrete and steel, bricks and mortar and
- Plastering, painting, flooring, and other items.

2.Literature review

The natural capital of the land is wincing owing to the use of sustainable and uncontrolled human resources resulting from population growth. At a rate that exceeds the ability of the Earth to replenish, resources such as raw materials, fuels, biomass, and water are being continuously drawn. Pollution, greenhouse gas emissions, waste generation, and land degradation are the major effects of this increased resource use, as is also supported by studies [27, 28]. The consumption of energy in the activities building like transport, construction, and construction is a significant contributor to the global emissions of CO_2. By the end of 2050, the worldwide population is anticipated to reach 10 billion people. It is vital to note that a large amount of this growth is occurring in countries where the amount of international CO_2 emissions is the highest. A few research reports [29, 30] have quantified the total energy use of different structures during their lifespan across different scales about the built environment or the combined life period power and expense analyses.

Norman et al. [31] have compared the life pattern power usage of large structures around Toronto, Canada, including transport demands. However, their research, particularly underestimates embodied demands.

Fuller and Crawford [32] have analyzed the life cycle of power, i.e., the total and greenhouse gas emissions of various housing patterns close to Melbourne, Australia. This is undoubtedly an extensive study for quantifying EE. However, their research does not perhaps examine the power consumed in certain practices and their financial feasibility because they depend on hybrid (EE and OE).

Stephan and Crawford [33] and Stephan et al. [34] have studied the life of the total power profile of various residential structures in the Australian Continent, Belgium, and Lebanon, including embodied, operational, and transport requirements. However, they have not considered the financial requirements in their scientific studies.

A considerable amount of energy (40%) and non-energy sources such as construction equipment, water (16 %), fuels, electricity, and labour are consumed by the construction industry [35, 36], which contributes to CO_2 emissions and waste generation. Approximately 40 % of the global supply of raw stone, gravel, and sand, and 25 % of natural timber are reduced each year owing to building activities [37, 38]. Buildings utilize energy during the construction, operation, maintenance, remodelling, and demolition phases of their life cycle. Energy is also consumed in producing construction materials. Widely used building materials, such as cement, steel, aluminum, and insulation, are potent [39].

All the products and procedures used for constructing a building comprise the early EE [40]. This factor is also maintained and restored when the building is occupied, and some parts are periodically replaced. These processes, known as repetitive EE, directly and indirectly consume energy [41]. When a building is demolished during the final stage of its life, the materials used in it comprise direct and indirect energy that is either to be recycled, has been recycled, or disposed of. This component of energy is called the dissipation force [42, 43]. The entire life cycle is the sum of the EE of the initial, repetitive, and demolished energy of a building [44, 45]. The energy consumption during the entire life cycle of a building involves EE and OE. The OE is consumed in lighting, air conditioning, and power building equipment. EE and OE computation play a significant role in choosing the right materials required for reducing energy consumption and making the construction sector eco- and environmental-friendly. Similarly, utilization of industrial by-products as alternative building materials reduces the challenges of disposal of waste by-products and reduces the energy consumption required for manufacturing the same. Likewise, this study attempts, in the Indian context, to reduce the OE and EE in the building sector for selecting the right materials for construction by considering a typical ground + three floors residential buildings in Vijayawada City of Andhra Pradesh.

3.Methodology

This section describes the methodology adopted for computing the EE and OE for a typical mid-rise urban residential building in the Indian scenario. *Figure 1* depicts the method adopted in the present study.

3.1Case study of a residential building located in Vijayawada

The residential building considered for the study is located at Vijayawada City, Andhra Pradesh, India. *Figure 2* exhibits the typical floor plan of a residential building. The building is an RCC framed structure and comprises three floors, including a stilt and open terrace. Each floor consists of three bedrooms, a hall, a kitchen, and a balcony. Front view of the house is shown in *Figure 3*, which presents the precise dimensions of the building, including the thickness of the walls. The drawing was prepared after doing manual measurements for each floor, where various structural components of the building were identified and computed. The selection of the building materials is important for reducing the transportation cost and the overall cost of the material. Building materials such as bricks, steel, cement, and other materials were procured from the local market. The EE of each building material involved in the structure was identified from the literature [46, 47], computed, and aggregated to calculate the total EE.

3.2 Computation of EE of the residential building

The EE values of various materials were computed for the residential building considered for the study. The values of EE were taken from the literature [47], considering the Indian scenario. *Table 1* lists the EE values of different building materials considered from the available studies [46, 47]. The values computed are the upper bounds wherever multiple reports are available. Manual measurements were done for each floor, and various structural components of the building were computed manually. Primary building materials were tabulated. *Table 2* lists the EE values of the quantified materials for the residential building.

3.3 Computation of OE of the residential building

Unlike EE, the consumption of OE depends on the occupants of a building. The energy required during the lifespan of a building from its commissioning to its end of life, not including renovation and maintenance, is defined as OE. The computation of OE is relatively simple compared to that of EE. The energy used to cool/heat the premises, hot water, lights, etc., is computed while the building is in use. Out of the total primary energy consumption, 37% of the total consumption in India is by the residential sector. *Table 3* gives the OE values of the components used in the residential building considered in this study. Among the components, Air Conditioners (ACs) contribute the most to energy consumption, i.e., 49%, almost half the total OE. The significant components apart from

ACs are refrigerators, lights, geysers, and fans in decreasing order. The total annual OE is 128.67 GJ, and the OE for a building in use (50 y) is 6433.5 GJ.

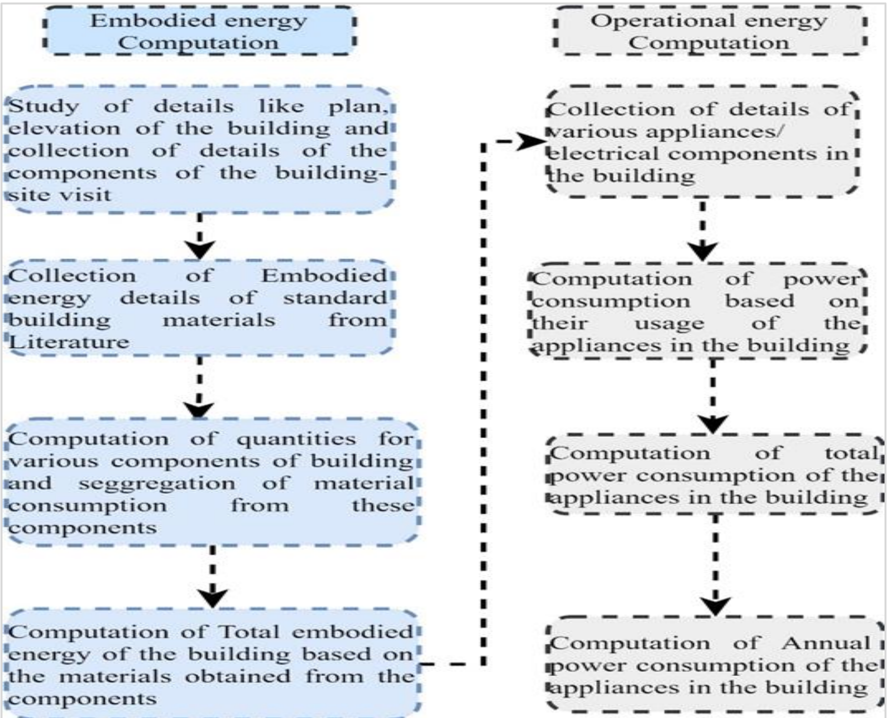

Figure 1 Methodology adopted for the present study

Table 1 Embodied energy values considered from the studies [46, 47]

Material	Unit	Embodied energy (MJ/ Unit)
Cement	kg	6.4
Sand	kg	0.11
Coarse aggregate	kg	0.11
Steel	Kg	30.0
Bricks	No	4.4
Paint	sq.m	39.24
Floor Tiles	sq.m	157.4

Table 2 Embodied energy values of the materials quantified for the residential building

Material	Quantity (Units)	Embodied energy (GJ)/Unit	Embodied energy of materials (GJ)	% of Embodied energy	Remarks
Cement	146253 (kg)	0.0056/kg	936.0	36.18	Concreting for RCC components, PCC work, plastering, brick masonry work
Sand	624716 (kg)	0.11/ton	68.7	2.66	Concreting for RCC components, PCC work, plastering, brick masonry work
Coarse aggregate	520151(kg)	0.11/ton	57.2	2.21	Concreting for RCC components, PCC work,
Steel	28500(kg)	30/ton	855.0	33.05	RCC component in Foundation, Columns, Beams, Slab
Bricks	100435(Nos)	0.00425/no	442.0	17.09	Brick work in sub and super structure

Material	Quantity (Units)	Embodied energy (GJ)/Unit	Embodied energy of materials (GJ)	% of Embodied energy	Remarks
Paint	2257 (sq.m.)	0.03924/sq.m	88.6	3.42	
Floor Tiles	885 (sq.m.)	0.1574/sq.m.	139.3	5.38	
Total Embodied Energy			2586 GJ		
Total Embodied Energy in GJ/m^2			3.1		

Table 3 Operational energy values of the components used for the residential building

Component	Number	Energy consumption (W)	Usage (hour/day)	Total power consumption (W)	Annual energy consumption (MJ)	Operational energy (%)
Fan	14	60	6	840	6623	5.1
Light	50	30	7	1500	13797	10.7
Geyser	3	1000	2	3000	7884	6.1
A C	3	2000	8	8000	63072	49.0
Refrigerator	3	240	24	720	22706	17.6
Television	3	80	7	240	2208	1.7
Washing Machine	3	280	1	840	1104	0.9
Exhaust fan	40	4	120	631	3	0.5
Mixer grinder	400	0.5	1200	788	3	0.6
Lift	1	3750	2	3750	9855	7.7
Total Annual Energy in GJ					128.67	
Operational Energy (50 Years) in GJ					6433.5	835 m^2
Operational Energy in GJ/m^2					7.70	
Operational Energy for AC in GJ/m^2					3.78	

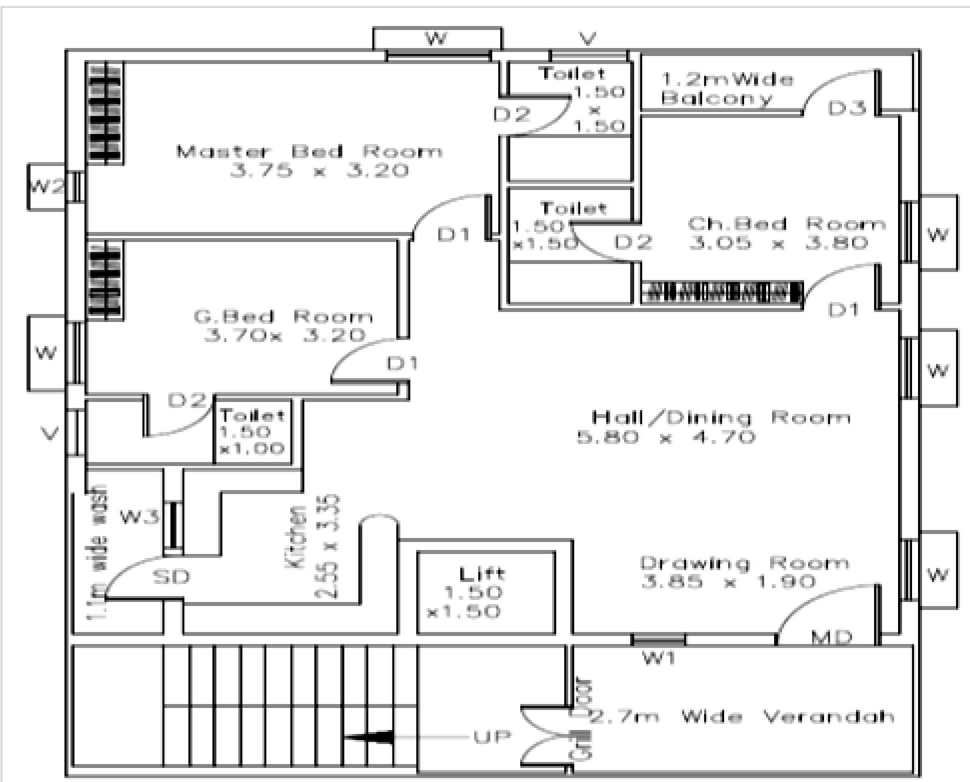

Figure 2 Typical floor plan of the Residential building considered for the study


Figure 3 View of the Residential building considered for the study in the city of Vijayawada, Andhra Pradesh

4.Results and discussion

4.1Embodied energy

From *Table 1*, it can be seen that the cement used for the building contributes 36% to the total EE, followed by steel (33%) and bricks (17%). The total EE is computed to be 3.1 GJ/m2. Apart from the above three components, building materials such as floor tiles and aggregate contribute approximately equally, and their total contribution is approximately 10%. The percentage contribution of painting is about 3.4%. Timber and glass contribute to less than 0.1% and hence have been neglected in this study. The percentage contribution of each of these materials is shown in *Figures 4*. The EE computations show that a significant amount of energy is used for materials such as cement, steel, and bricks. In their place, the use of alternative building materials and technologies can help to reduce the value of EE. For example, if a fly-ash or Ground-Granulated Blast-Furnace Slag (GGBS) is used as a partial replacement (up to 30%) for cement, the value EE reduces from 36% to 30%, which is a reduction of 17% in the EE of cementitious material. For masonry work, if a hollow concrete block is used in place of burnt clay brick, the EE values, reduce from 17% to 6%, a reduction of 64% in the EE value.

4.2Operational energy

As the total OE is approximately 3.76 GJ/m2, without AC, only OE of AC load is 3.78 GJ/m2. *Figure 5* exhibits the percentage annual OE values for the various components of the building. The AC load contribution to the OE value of a typical residential building in a city located in a hot and dry region such as Vijayawada is almost equivalent to the total load value. This clearly shows that the thermal comfort of the building is considerably affected, and significant load results from cooling the rooms from the inside. Measures need to be taken to reduce the heat transfer in the building through the building envelope. Various methods are available to control the heat flow through the building fabrics, such as walls and roofs. By incorporating hollow blocks and Solar Reflective Index (SRI) paints, the thermal comfort inside the building can be improved. Similarly, for the roof portion, the methods such as cool roof coating and glazed reflecting tiles will improve human comfort inside the building. The EE content is incurred once apart from maintenance and renovation, whereas OE accumulates with time and can be affected throughout the lifespan of the building.

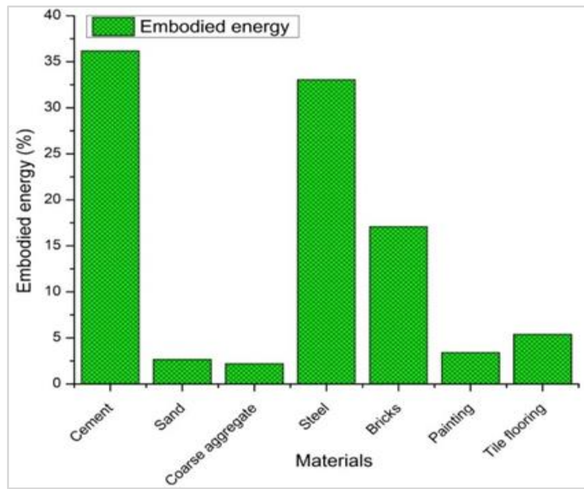

Figure 4 Embodied energy (%) of various building materials used in the building

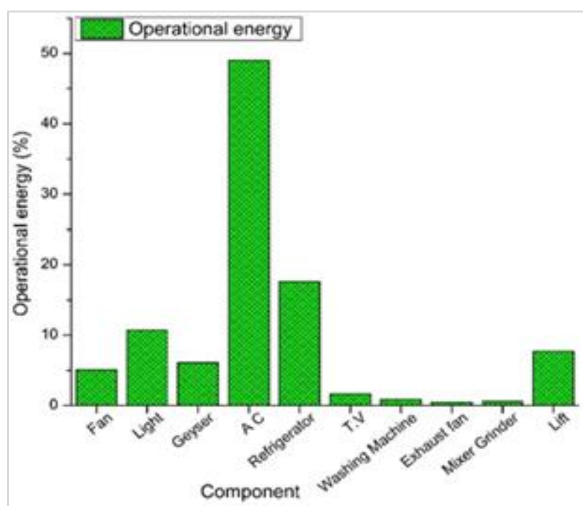

Figure 5 % of Annual operational energy values for various components of the building

5.Conclusions

After a detailed computational analysis, it can be concluded from this study that limiting the energy demand and controlling environmental pollution has a significant effect on climate change. The contribution from the construction sector to these factors is substantial and optimum strategies are required to control them. In this study, an attempt has been made to compute the EE and OE values of a residential building situated in Vijayawada, Andhra Pradesh. In particular, the EE values of the various building materials have been estimated in this work. The case study chosen here is an exciting example of an RCC structure with ground + three floors. The cement used for the building was observed to contribute 36% to the total EE, followed by steel (33%) and bricks (17%). The total computed EE was calculated to be 3.1 GJ/m2. Alternative measures for reducing the EE in buildings, including the usage of recycled materials, transportation, using solar energy, replacing cement with fly-ash and GGBS, building interior products, should also be considered. As the total OE is calculated to be approximately 3.76 GJ/m2, without AC, the only OE of AC load is calculated to be 3.78 GJ/m2. The AC load contribution to the OE for a typical residential building in a city located in a hot and dry region such as Vijayawada is almost equivalent to the total load. This clearly shows that the thermal comfort of the building is significantly affected, and considerable load results from cooling the rooms in the building from the inside. Measures must be taken to decrease the heat transfer in a building through the building envelope. The EE content is incurred once apart from the upkeep and renovation, whereas OE accumulates over time and can be affected throughout the lifespan of the building. This study quantified the lifespan that is the energy and cost and steps to minimize by concentrating on embodied, useful, and transportation of energy requirements. This tends to be meant by this comprehensiveness being many with lowering energy use and effects and that can be linked ecological you appear in the built environment are usually grabbed simultaneously. It permits testing of various energy reduction actions together with the identification of the most economical and useful steps. This study offers a foundation for future power reduction strategies for residential structures by giving recommendations for reducing energy consumption to every single contributor associated with the built environment centred on the quantified benefits. This can ultimately reduce the adverse impact of energy consumption on the environment and create a healthier built environment.

5.1 Scope for future work

- This study included computation of EE and OE for a typical mid-rise urban building in India comprising of ground plus three stories and using a conventional RCC framed structural system. This work can be extended by comparing the EE values for a load-bearing structural system consisting of stabilized mud blocks/hollow concrete block systems.
- Since the roofing system in a typical building consumes a considerable amount of material, such as steel and concrete, studies can be carried out by considering alternative roofing materials, such as filler slabs, jack arch roofing, and study their impact in reducing EE.
- Studies can be conducted to find the relationship between EE, OE, capital cost, and maintenance cost. The impact of cool roof coatings in reducing the OE of the building can be done in future studies.

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None.

Conflicts of interest

The authors have no conflicts of interest to declare.

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Appendix I

S. No.	Abbreviation	Description
1	AC	Air Conditioner
2	CO_2	Carbon Dioxide
3	EE	Embodied Energy
4	GJ	Giga Joules
5	GJ/m^2	Giga joules per square meter
6	kg	Kilogram
7	m	Meter
8	MJ	Million joules
9	m^2	Meter square
10	No.	Number
11	Nos	Numbers
12	OE	Operational Energy
13	PCC	Plain Cement Concrete
14	RCC	Reinforced Cement Concrete
15	SRI	Solar reflective index
16	sq.m	Square meter
17	ton	Tonne