Embodied Energy and Carbon footprints in Residential buildings

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***Abstract*— *To satisfy the housing needs of an ever increasing population, the construction of buildings have become a large consumer of a considerably large amount of energy and resources. This human activity as well as other industrial and domestic activities if left unchecked will result in the gradual deterioration of our environment. The term embodied energy has been developed as a means to measure the energy expended during the life cycle of a building material. This life cycle consists of mining and processing of raw materials, production processes which transforms the raw materials to the desired building material, transportation to site, construction and finally demolition. The use of embodied energy as a measurement tool is currently being applied in other industrial sectors such as manufacturing and road construction. This paper aims at calculating the embodied energy and carbon footprint of a 1 bedroom 1 storey flat. Results obtained from this analysis reveal that the embodied energy and carbon of the case study building is $2878.32MJ/m^2$ and $367.21kgCO^2/m^2$ respectively.*

Keywords—Embodied energy, Embodied carbon, life cycle, buildings

I. INTRODUCTION

In the world today, most residential buildings as well as industrial buildings have been constructed in disregard for their environmental impact. Evidence of the overwhelming signs of climate change are now disseminated(Government, 2006),(COST, 2009) furthermore, it is widely accepted that human activities has been largely responsible for this environmental change and therefore policies have been developed aiming to reduce the problem (Abanda, Nkeng, Tah, Ohandja , & Manjia , 2013). The building sector is largely responsible for such negative environmental impact (Li 2006, Stephan et al, 2011), therefore people involved in the development of buildings have a great responsibility toward achieving sustainability standards.

Overtime, buildings construction have neglected the high emission of greenhouse gases by the construction materials used due to their high embodied energy associated with them. The current estimates of embodied energy in housing vary significantly. Ravtez, 2008 gives construction carbon emissions as 27% of the lifetime emissions cradle to grave emissions). Since the realization of the environmental impact of greenhouse gases emissions emanating from the building industry, much effort has been focused towards improving the design of materials of buildings in order to reduce their operational energy (Stephan et al 2011, Yeo & Gabbai, 2011). However, these efforts resulted in these materials having higher embodied energy (TargetZero, 2012). The most important factor in reducing the impact of embodied energy is the design of long life, durable and environmentally adaptable buildings. Every building is a complex combination of many processed materials, each of which contributes to the building's total embodied energy. Renovation and maintenance also adds to the embodied energy of a building's life.

Buildings alone are responsible for 38% of all greenhouse gases caused by human activities (20% residential, 18% industrial). It is the industrial sector which contributes the most to climate change. Greenhouse emissions associated with building construction (residential and industrial) construction originates mainly from the material manufacture stage, material transport, demolition wastes transport and finally where applicable demolitions and waste treatment. The construction, renovation and deconstruction of a typical building on the average are responsible for emissions ranging from $1000kgCO_{2e}/m^2$ to $1500\ kgCO_{2e}/m^2$. Construction alone is responsible for as much as $500\ kgCO_{2e}/m$.

1.1Embodied energy

Buildings are constructed with different building materials, each of which is responsible for some degree of energy consumption during its life cycle stages. These life cycle stages include; raw material extraction, transport of these raw materials, manufacture, assembly, installation, demolition and in some cases disposal. (Dixit, Fernández-Solís, Sarel, & Culp, 2010). The term embodied energy is subject to different interpretations rendered by different authors and its published measurements are found to be unclear (Miller, 2001). Saman& Ting, 2007 states that total energy consumption of a building, which has a direct impact on its carbon footprint, is a combination of both embodied energy and operational energy. Energy expended during the maintenance of the inside environment of a building through processes such as heating, cooling, lighting and operating of building appliances is referred to as operational energy. Figure 1 shows the embodied energy of materials in a typical building.

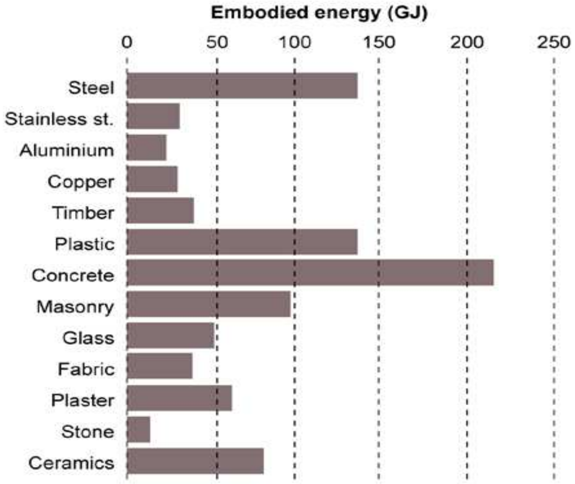

Fig.1: Levels of embodied energy for materials used in a typical residential building
Source: CSIRO

According to Hegner 2011, only energy that is available for a limited amount should be considered as embodied energy. This explanation relates the phenomenon of embodied energy to greenhouse gases emission, as a major fraction of primary energy that is available in a limited amount comes from fossil fuels. Research by M.K Dixit, shows that the total life cycle of a building includes both embodied energy and operational energy. Embodied energy can be regarded as the sum of all the energies consumed by processes associated with the production of a building, from mining and processing of natural resources to manufacture, transport and product delivery (Geoff & Reardon, 2013). There are two forms of embodied energy, initial embodied energy which is the energy consumed during the production of materials and components and also includes raw material procurement, building material manufacturing and finished product delivery to the construction site. (M.K Dixit, 2012). The other form which is recurring embodied energy. Recurring embodied energy is the non-renewable energy used in various maintenance and refurbishment processes during the useful life of a building.

In the analysis of embodied energy, 3 methods currently exist; Process analysis, Input-Output analysis and Hybrid analysis. Process analysis method of embodied energy begins with the final production process and works backward to the point of raw material s extraction in other to determine the entire energy needs of each contributing material or energy input (Gustavsson & Sathre, 2004). It is the oldest and still most commonly used method of embodied energy analysis. As the analysis expands to include the energy consumed by higher order indirect inputs, the contribution of additional factors becomes less significant and more cumbersome to determine. Input/output analysis is a method of embodied energy analysis method that uses a systematic approach to model the flow of products between sectors of an economy (Graham, 1998). Unlike the process method which relies on the processes involved in the production process of a commodity, the input/output (I-O) approach uses national statistical tables and figures of monetary value to assess energy inputs and outputs of particular goods or services (Crawford, 2009) . Input-output embodied energy analysis was originated by 1973 Nobel laureate in economics, Wassily Leontief in 1971. Leontief's input-output model was in turn an adaptation of the neo-classical theory of general equilibrium with application to "the empirical study of the quantitative interdependence between interrelated economic activities (Leonteif, 1966). Leontief made use of the input-output tables which shows the exchange of goods and services among industrial sectors in an economy presented in matrix form (Keisuke et al 2002). Adolf Acquaye 2010 defines the input-output table as a summary of all the deliveries between producer, trader and consumer. He further stated that it is an economic map broken down into various sectors and the inter-relationship between all the economic sectors. The disadvantages of the process analysis and input/output analysis have been reduced by the hybrid analysis method which combines both the process and input/output analysis (Menzies, 2011). This hybrid analysis eliminates the shortcomings of the constituent methods of analysis. There are several hybrid embodied energy methods which depends on the way the parent embodied energy analysis methods (process and input/output analysis) are combined (Acquaye, 2010). According to literature, the results of the series of combination give rise to the following hybrid analysis methods;

a. Process based hybrid analysis
b. Input/output based hybrid analysis
c. Tiered based hybrid analysis
d. Integrated hybrid analysis

II. METHODOLOGY AND DATA COLLECTION

For the purpose of this study, data used for the evaluation of the embodied energy and embodied carbon associated with the case study buildings are;

1. The Inventory of carbon and energy, which is an open-access database for embodied energy and carbon dioxide emissions associated with materials used in the construction industry. It was developed by Geoffrey Hammond and Craig Jones (Hammond & Jones, 2008) in 2008 and later revised in 2011. The Inventory of carbon and energy is a spreadsheet format database which shows the embodied energy coefficients as well as the embodied carbon coefficient to calculate the value of the embodied energy and carbon of construction materials and alternatively building dwellings.
2. The case study building's bill of engineering measurement and evaluation (BEME). This contains the unit measurement of each material used in the building construction. These units (usually specified in mass (kg) or volume (m^3) is combined with the embodied energy and carbon coefficients to obtain the embodied energy and carbon associated with the building material in question.
3. CIBSE Concise handbook 'A' which contains the densities of different materials used in building construction.

2.1 Steps of the methodology

The series of steps taken during the execution of the research are outlined below;

1. Model formulation according to literature that relates the masses of each building material to embodied energy and embodied carbon.
2. Data collection. The data collected have been outlined in the section above.
3. Evaluation of the embodied energy and embodied carbon of the case study buildings.

The model that will be used to evaluate the embodied energy and carbon for the case study building is given below;

$$E_E=\sum_{i=0,1,2.....n}^{n} E.Ei(Q) \qquad (1)$$

Where E_E=Total Embodied energy

n= Total number of materials

Q= Material quantity

$E.Ei$= Embodied energy of each material

$$E_C=\sum_{i=0,1,2.....n}^{n} E.Ci(Q) \qquad (2)$$

Where E_C= Total Embodied carbon

$E.Ci$= Embodied carbon of each material.

For the successful application of the above model for the calculation of the embodied energy, certain assumptions were made. These assumptions were;

1. The boundary conditions used for the embodied energy and carbon coefficients in the ICE database were assumed to be the same for the building material construction in Nigeria.
2. The analysis of the Embodied energy and carbon is based only on cradle-to-gate conditions. This is due to the fact that energy analysis that would be done after the materials leave the factory gate would be difficult and unpredictable due to the fact that transportation and construction energy analysis will be the paramount analysis that will be conducted once the products leave the factory.

2.2Case study building

A typical residential building was chosen as the case study. The building in this case is a 1 bedroom 1 storey block of flats. Each floor of the building consists of 2 flats. The total area of the building is 323.89m^2 (148.0m^2 for the ground floor and 175.81m^2 for the first floor. Figure 2 and 3 below represents the ground and first floor building plan of the case study building.

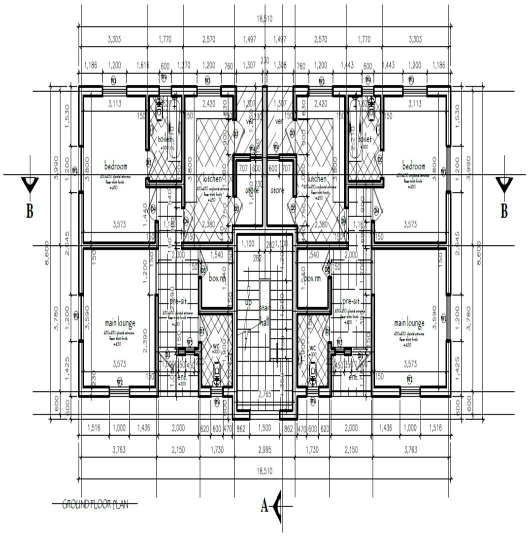

Fig.2: Ground floor plan

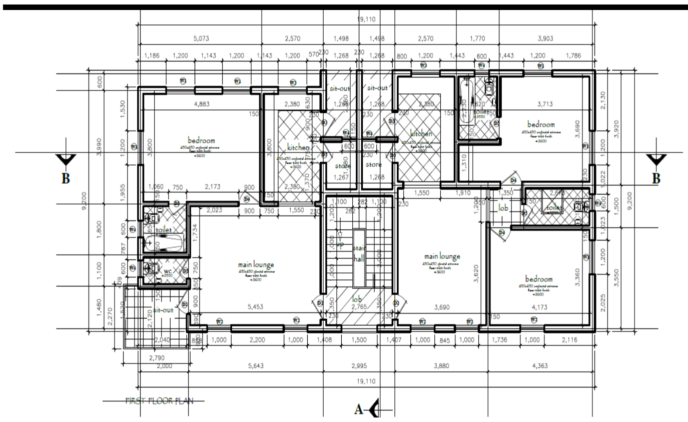

Fig.3: First floor plan

The foundation which is composed of reinforced concrete in the ratio of 1:2:4 (Cement: fine aggregate: coarse aggregate). Block work is done in the ratio of 1:4 (cement: sand) which is usually laid in coaches to DPC level. The outer and inner walls which are basically composed of block work in its majority. This block work as stated earlier is of the ratio of 1:4. The lintels are composed of reinforced concrete of 1:2:4. The roofing section which is composed basically of the roofing members (usually wood in the case of most residential buildings) and aluminium sheet covering. Occasionally, block work is done and this is referred to as gabble roof which is usually of the ratio of either 1:4 or 1:6 (cement: fine aggregate).

2.3Calculation of mass, embodied energy and embodied carbon

According to literature, the embodied energy and embodied carbon of building materials is determined by the combination of the embodied energy/carbon coefficients with the masses of the respective building materials (Abanda et al 2013). The masses of the reinforcements used in the building construction process are specified in the BEME are specified in kilograms (kg) which makes it quite straight forward in the determination of the embodied energy and embodied carbon through the application of the mathematical model described above.

All other materials used specified in the BEME are specified in area (m^2) or volume (m^3). As will be shown in the BEME, the materials which are specified in meters usually have their thickness specified which makes obtaining their volumes possible ($m \times m^2$).

III. RESULTS AND DISCUSSION

For the chosen case study as described in the methodology, the BEME was obtained which applying the mathematical model in equation 1 and 2 obtained the result as shown in table 1.

Table.1:Results showing the embodied energy and embodied carbon of the case study building.

Material	Mass (kg)	Embodied Energy (MJ)	Embodied Carbon $(kgCO_2)$
Foundation	150682.00	163873.00	23444.27
Frame	124168.20	246864.30	25336.54
Wall	303675.00	398907.90	62765.76
Roofing	1902.25	122615.39	7387.57
Total	***580427.45***	***932260.59***	***118934.14***

The embodied energy and carbon of the building obtained as described in the methodology was split into four sections, foundation, frame, wall and roofing. The total embodied energy and embodied carbon for the building as seen in table 1 are 932,260.59MJ and 118,934.14$kgCO^2$. The embodied enery and carbon calculated for a specific building should be measured per unit area of the said building. Therefore, in order to calculate the embodied energy and carbon of the building, the total embodied energy and carbon was divided by the area of the building. The embodied energy and carbon of the building becomes 2878.32MJ/m^2 and 367.21$kgCO^2/m^2$ respectively. The percentage of the total embodied energy and carbon of each section is seen in figure 4.

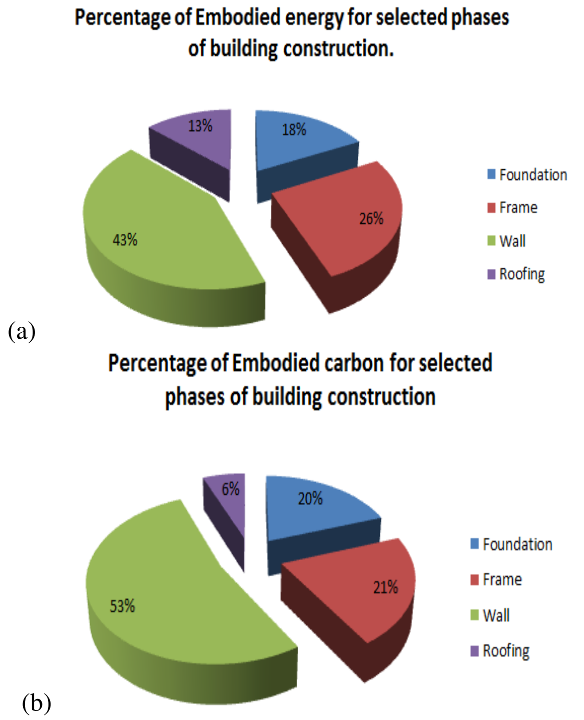

Fig.4: Percentage of the each section of the total Embodied energy and carbon

The results shown in figure 4 shows that the highest percentage of the embodied energy and carbon is in the wall and frames sections which are predominately composed of cement. It is also clear that the energy embodied in a building is directly proportional to the embodied carbon.

In order to effortlessly calculate the embodied energy, the materials are to be specified in kg. In the case of the BEME obtained for the case study, only the steel rods were specified in terms of their masses. The masses of the mortar, aluminium sheets and wood had to be obtained. This was made possible with the aid of the density of the respective materials. Using the equation for density ($\rho = {}^{m}/_{v}$, where $\rho =$ density, m =mass and $v =$ volume) and the volumes provided in the BEME, the masses were obtained.

Since the mortar was described as a ratio of their constituent materials (cement, fine aggregate and coarse aggregate). Their constituent masses had to be obtained by taking the ratio of the total mass which was used to obtain their embodied energy as specified in the Inventory of Carbon and Energy. This can be seen in table 2.

Table.2:Embodied energy and carbon of the constituent materials of the case study building

Material	Mass (kg)	Embodied Energy (MJ)	Embodied Carbon ($kgCO_2$)
Cement	100710.27	115815.72	18187.84
Aluminum	714.43	110737.19	6544.21
Steel	7932.00	138016.80	10390.92
Wood	5281.02	52810.20	3749.53
Fine aggregate (sand)	339892.57	411645.03	65441.11
Coarse aggregate (gravel)	125897.15	103235.65	14620.76
Total	***580,427.45***	***932,260.59***	***118,934.14***

The embodied energy and carbon of items such as ceiling boards, electrical fittings and plumbing weren't included in this analysis due to lack of adequate data.

From the analysis conducted, it is evident that the material with the highest embodied energy is the mortar which consists of cement, coarse and fine aggregates. It is recommended by virtue of the results obtained that more research should be conducted for the development of alternative materials with lower embodied energy.

IV. CONCLUSIONS

The analysis conducted as evident in the results obtained for all the case studies shows that there is a direct correlation between the embodied energy and embodied carbon. The embodied energy and embodied carbon are directly proportional to each other.

The results obtained also shows that for a typical building construction in Nigeria, the highest value of embodied energy and embodied carbon are in the concrete mixture. More research will be carried out to obtain the data for more building materials in order to conduct a complete analysis in order to obtain the embodied energy and carbon of residential buildings.

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