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THE SIGNIFICANCE OF EMBEDDED ENERGY FOR BUILDINGS IN A TROPICAL COUNTRY

by

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ABSTRACT

A computerised relational database management system is used to represent and calculate the embedded energies and carbon coefficients of building materials. The embedded energy requirements are also calculated on the basis of the lowest quality energy (called "bio-equivalent" energy), in addition to the more conventional basis of Tonnes of Oil Equivalent. Comparisons are then made between alternative materials for building components such as purlins, walls, roofs and windows. Among the more common construction materials considered, the lowest energy option is timber while the highest is steel, with concrete in between. Timber products have negative carbon coefficients as well, i.e. they store more carbon than is emitted in their use for house building. The walls and wall plastering contribute significant proportions of the gross energy of a building, indicating that the use of low energy materials for walls and the elimination of wall plastering will make significant contributions to reducing the embedded energy of buildings. The ratio between total embedded energy and annual operational energy for selected buildings ranges from 14 to 35 for the houses, while for an office building with air-conditioning loading it is 5.

INTRODUCTION

Energy and environmental considerations are becoming increasingly important today. This is primarily because there is an appreciation of the non-renewable and limited nature of many of our energy resources and environmental assets. However, any sort of development inevitably consumes energy resources and depletes environmental assets. This is particularly true of industrial development, and the construction industry is one of the largest contributors to Gross Domestic Capital Formation in many countries. As such, the above concerns regarding energy and environmental issues should particularly be applied to this industry as well.

Most of the construction industry energy considerations have been made with respect to the operational phase - e.g. energy saving buildings [1]. In cold countries such as U.K. and U.S.A. the ratio between construction and annual operational energy is around 3 to 6; in a temperate zone country that is a little warmer such as New Zealand [2], this ratio goes up to around 9. However in a tropical country such as Sri Lanka, the operational energy is likely to be very small as very little heating is required. This means that the energy embedded in the building assumes much greater significance. Therefore there is a clear need for research to be carried out into energy inputs and environmental costs of building materials, in order for building construction industry professionals and policy makers to make choices regarding the type of building materials that should be used.

The construction or embedded energy of building materials will vary from one country to another, depending on the sources of energy used for manufacturing [3]. In Sri Lanka, for example, there is a wide range of energy sources used for building materials manufacture, from firewood for brick and tile production to fossil fuel and electricity for cement and steel production. An energy policy would clearly need to take into account such differences in quality of the energy sources [4,5] that are used for manufacture, and not merely the quantity. There is also the issue of the energy of imported building materials or raw materials. The question arises as to how concerned we should be about energy contents in such materials, as the actual energy expenditure is not incurred within the country.

OBJECTIVES

The objectives of the research described in this paper are as follows:

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1. To obtain values for embedded energies and carbon coefficients of building materials.
2. To compare the embedded energy contents of building materials in a way that reflects the quality of the energy sources used.
3. To compare energy contents and carbon coefficients for alternative materials of construction.
4. To find the gross embedded energy input to typical residential and office buildings.
5. To find the influence of various building components on the embedded energies of residential buildings.
6. To compare the significance of construction energy with that of operational energy in Sri Lanka.

METHODOLOGY

ENERGY ANALYSIS

Although there are many ways of carrying out energy analyses [2], process analysis is used in this study, following Honey and Buchanan [6]. The energy requirements for a given product output can be determined fairly easily by field visits to identify all the material and energy inputs into the process. Also, following Baird and Chan [2] and most other workers, human energy and energy associated with environmental costs, though advocated by Odum [4], have not been included in the energy analysis, mainly because of the complexity and ambiguity associated with such factors. However, this study does make an independent assessment of environmental costs in terms of Carbon dioxide emissions.

SYSTEM BOUNDARIES

The IFIAS workshop [7] suggested that four boundary levels can be drawn for most materials [8]. In general a process will require decreasing amounts of energy with an increase in the boundary level. Process analyses [2] are commonly used to calculate energy requirements at Levels 1 and 2. Level 1 includes the direct and transport energy inputs to the process, while Level 2 also includes the energy required to make the material inputs to the process. As much as 90 percent of the total energy sequestered in the process should have been included in the first two levels [7]. This study was aimed at capturing energy inputs into building materials up to Level 2.

TOE VALUES AND CARBON COEFFICIENTS

In order to compare energy values from different sources, a common unit, i.e., Tonnes of Oil Equivalent (TOE) is used. For example, 1 metric tonne (MT) of diesel has a TOE value of 1.05, while 1 MT of firewood has one of 0.38. One TOE is equivalent to 41.84 GJ.

A TOE value of 0.086 for 1 Mwh of hydro electricity, based on a "100% efficiency", is commonly used, although it lacks theoretical rigour. It is arrived at by a comparison with oil based electricity which has a 36% efficiency and a TOE value of 0.24 for 1 MWh. Losses of energy in the production and transmission of hydro electricity are not accounted for here; neither is the energy for extracting and transporting all other energy sources (since these components are comparatively small). For the conversion of Sri Lankan electricity consumption into TOE values, it is taken that 66% is hydro electricity and 34% is thermal [9], thus yielding a TOE value of 0.138 (or 5.78 GJ/MWh).

The gross quantity of Carbon (mostly in the form of Carbon dioxide) emitted in the manufacture of each material per unit of weight or volume is termed the "Carbon Coefficient". Most of the carbon emissions arise as a result of the burning of fossil fuels. The conversion factors used in this study (after Turbott et al. [10]) are 20.3 kgC/GJ for oil type fossil fuels and 54 kgC/GJ for thermal electricity (and of course zero for hydro electricity); since 34% of electricity is taken as thermal, a value of 18.36 kgC/GJ of electricity was used.

Burning of wood emits carbon dioxide too, but no more than was absorbed when the tree was growing - i.e. 250 kg of carbon is stored per cubic metre of wood; so wood fuels are sustainable, giving a net value of zero kg of carbon per unit of biomass energy.

Apart from this, any timber used in construction is considered to "lock up" carbon and contributes a negative carbon coefficient equal to the value above. Such locking up is not ascribed to formwork, which has a very short life span and will hence release carbon to the atmosphere fairly soon by decay or other means. Carbon is locked up in steel too, but the amount is negligible and hence ignored.

Carbon dioxide is also released to the atmosphere via chemical reactions in the aluminium and cement industries. Therefore a figure of 130 kg of carbon per tonne of aluminium was included in the carbon coefficient for aluminium and a figure of 142 kg of carbon per tonne of cement was included in the carbon coefficient for cement [6].

In order to obtain carbon coefficients from energy intensities for imported items, the embedded energy was multiplied by a factor of 20 kgC per GJ based on a report by Honey and Buchanan [6].

CALCULATION OF ENERGY CONTENTS AND CARBON EMISSIONS

The energy embedded in a building material will in general comprise (i) production energy, (ii) energy to transport its component materials and (iii) the energy embedded in its component raw materials (with the energy to extract and transport energy sources being ignored). All these energies can also be classified according to input energy type as biomass, fossil fuel and electrical energy. Figure 1 shows this schematically for the brick wall element. In addition to biomass, fossil fuel and electricity, the database (described below) has a field for "imports" (i.e. raw materials imported to the country), and another one to account for carbon emissions (or storage) not related to the fuel type. These fields are not represented in Figure 1 for the sake of simplicity. Each energy component (whether classified by process or fuel type) also has a minimum, average and maximum value, since a number of samples were used to arrive at the energy contents.

DATABASE OUTPUTS

The above data was stored in a computerised database [8]. Reports were used to show summary information relating to the data. These reports summarise the embedded energy of each item for a defined quantity in terms of,

(i) different fuel types, i.e. biomass, fossil fuel, electricity and imports, and

(ii) different processes, i.e. production, transport of raw material and the energy embedded in raw materials.

In both reports these different energy categories are shown as minimum, average and maximum values, and the total minimum, average and maximum embedded energies of each item are also given.

Reports were also used to give the carbon coefficients, consisting of the carbon emissions from (i) all the fuels (i.e. biomass, fossil fuel, electricity), (ii) imports, (iii) particular carbon liberations or locking up (i.e. from the "material"), and finally (iv) the net value of each item for a defined quantity.

Tables 1 and 2 show the ranges of energy contents and carbon emissions respectively obtained in this study; they also compare these values with other researchers' results. These tables broadly indicate that the values obtained in this study are consistent with those of others.

Table 1
Energy Contents of Building Items

Items	*Samples*	*Qtty*	*Total Energy(MJ)*			*Other Researchers*	
			Min.	*Avg.*	*Max.*	*Values (MJ)*	*Reference*
Aggregates	2	1 m^3	87	99	111	29-115	Clough & Martyn [17]
Asbestos Sheets	2	1 MT	4,359	4,476	4,594		
Blocks 4"x8"x16"	2	1000	3,571	3,855	4,140		
Blocks 6"x8"x16"	2	1000	5,879	6,136	6,397	4,615	Baird & Chan [2]
Blocks 8"x8"16"	2	1000	6,070	6,341	6,612		
Bricks	5	1000	5,307	8,576	10,605	9,300-10,000	Baird & Chan [2]
Cement	1	1 MT	4,282	4,282	4,282	3,400-6,100	Clough & Martyn [17]
Concrete (1:2:4)	(BSR)	1 m^3	1,558	1,664	1,770	1,766-4,434	Baird & Chan [2]
Concrete (1:3:6)	(BSR)	1 m^3	1,179	1,284	1,390	1,324-1,840	Baird & Chan [2]
Glass	1	1 MT	8,342	8,342	8,342	13,900-22,100	Baird & Chan [2]
Paints-Emulsion	3	1 l	53	54	54		
Paints-Primer	3	1 l	124	125	125	20-150	Baird & Chan [2]
Timber Purlins (rough)	7	1 m^3	1,191	1,403	2,026	714	Baird & Chan [2]
Timber Planks (rough)	3	1 m^3	1,292	1,696	1,995		
PVC	3	1 MT	94,204	95,685	98,590	81,000-96,000	Baird & Chan [2]
Steel	1	1 MT	32,686	32,686	32,686	30,000-50,000	Spence & Cook [18]
Al extrusions	1	1 MT	147,477	147,477	147,477	145,000	Baird & Chan [2]
Plywood	1	1 m^3	12,090	12,090	12,090	9,500	Baird & Chan [2]
Brickwork 4.5"	(BSR)	10 m^2	3,471	5,452	6,698	10,000-11,920	Baird & Chan [2]
Brickwork 9"	(BSR)	10 m^2	6,968	10,893	13,364		
Soil (Clay)	5	1 m^3	1	4	11	0-100	Spence & Cook [18]
Timber Purlins (treated)	(BSR)	1 m^3	1,211	1,429	2,059	2,370-3,714	Baird & Chan [2]
Timber Planks (treated)	(BSR)	1 m^3	1,312	1,722	2,028		

Table 2
Carbon Coefficients of Building Items

Item	*Number of Samples*	*Qtty*	*Carbon Coefficient*	*Other Researchers Quoted by Baird & Chan [2]*	
			(kgC/Qtty)	*Range(MJ)*	*IFIAS Level*
Aggregates	2	1 m^3	2.00	5.45	4
Asbestos Sheets	2	1 MT	190		
Cement	1	1 MT	228	311	4
Concrete (1:2:4)	(BSR)	1 m^3	78	118	4
Concrete (1:3:6)	(BSR)	1 m^3	58		
Paints - Emulsion	3	1 l	1.1	0.19-0.23	4
Paints - Primer	3	1 l	2.49		
Timber Purlins (rough)	7	1 m^3	-281	-234	4
Timber Planks (rough)	3	1 m^3	-258		
PVC	3	1 MT	1907	1680	2
Steel	1	1 MT	652	610	4
Al extrusions	1	1 MT	3050	2530	2
Plywood	1	m^3	-347	-72	4
Soil (Clay)	5	1 m^3	0.1	3.83	2
Timber Purlins (treated)	(BSR)	1 m^3	-281	-228	4
Timber Planks (treated)	(BSR)	1 m^3	-258		

The database outputs can also be exported to a spreadsheet that contains a bill of quantities (BOQ) of a building. In this way, the variations in energy for alternative types of building materials (e.g. use of a block wall instead of a brick wall) can also be studied. The embedded energy of an entire building can be computed using the complete Bill of Quantities (BOQ).

ENERGY QUALITY ANALYSIS

Although it may seem that the least energy intensive material is the preferred option, there are other issues that have to be considered too. One of the main issues is regarding the differences in energy quality. For the purpose of this study the "quality" of energy is characterized by the concept that "a high quality energy or energy source can be used for a variety of end-uses with relative ease" [5]. Thus electricity (which has a wide variety of end-uses) has the highest quality while biomass the lowest (since burning is the only way it can yield its energy and because it cannot be easily transported and utilized like many fossil fuels).

The next step should be to find a methodology for comparing different energy qualities. One approach to this could be to assess the amount of the lower quality energy that is required to obtain a given quantity of the higher quality energy via established processes. All the energy requirements can then be compared on the basis of the total equivalent amount of lowest quality energy (i.e. biomass energy). The resulting energy values are termed "bio-equivalent energy" units.

It must be appreciated that the above analyses are essentially efficiency based analyses. The disparity between the qualities of biomass, fossil fuel and electricity based energy is likely to be greater than reflected by these efficiency calculations. For example Odum [4] values a unit of electrical energy at 4 times that of fossil fuel energy, whereas a purely efficiency based approach will result in a factor of only 2.78 (see below). This study adopts the efficiency based approach, because it has a clear basis and because it will not distort the original energy values too much.

Since electricity has the highest energy quality, it is used as a reference, and assigned an "efficiency" of 100%, whatever the primary fuel used for its generation; this is similar to the ideas associated with assigning a TOE value for hydro-electricity (discussed before).

In obtaining thermal electricity the conversion efficiency is assumed as 36%. Therefore, 2.78 GJ of fossil fuel energy will be equivalent to 1 GJ of electrical energy. The process of obtaining electricity by burning firewood (dendro-electricity) can be used to find the relationship between electricity and biomass. It can be shown that 1 GJ of electrical energy is equivalent to 5 GJ of biomass energy. Using the conversion of firewood to producer gas, it can also be shown that 1 GJ of fossil fuel energy is equivalent to 1.34 GJ of biomass energy [8].

For the system to be mutually consistent, the conversion from biomass to electrical energy through fossil fuel energy must be identical to the direct conversion from biomass to electrical energy. In order to do this, the fossil fuel to electricity factor was maintained at 2.78 (based on the 36% efficiency of thermal electricity), as it is fairly well established. The biomass to fossil fuel factor was increased from 1.34 to 1.8 in order to increase this "quality gap" rather than reducing the "quality gap" factor of 5 between biomass and electricity (i.e. 1.8 x 2.78 = 5).

The embedded energies of selected building items in terms of bio equivalent units are shown in Table 3, together with a comparison with their TOE values. It must be appreciated that this is a fairly simplified approach to energy quality analysis, as it uses only the first law of thermodynamics. A more sophisticated approach, not carried out in this study, would be to use the concept of exergy to quantify the thermodynamic potential of a system [8].

COMPARISON OF BUILDING MATERIAL ALTERNATIVES

PURLINS

The energy inputs and carbon emissions corresponding to purlins made out of 3 different materials, i.e. timber, steel and prestressed concrete, were analysed. The cross section of each purlin was selected so that it could carry a uniformly distributed load of 1 kN/m over a span of 3 m.

The cross section required for timber purlins is 75 mm x 100 mm. The cross section required for steel purlins is a 75 mm x 75 mm x 6 mm angle section. The cross section required for prestressed concrete purlins is 60 mm x 120 mm (grade 40 concrete) with 3 nos. 6 mm diameter high tensile wires.

The energy inputs corresponding to timber, prestressed concrete and steel purlins, which have similar spans and approximately similar bending capacities, are 29 MJ, 121 MJ and 654 MJ respectively in terms of TOE, indicating that steel is around 23 times more energy intensive than timber and that prestressed concrete is around 4 times more energy intensive than timber. However on the basis of bio-equivalent units the ratios are 15 and 3 respectively. It was also found that 5.6 kg of carbon is stored for the timber purlin compared to 3.7 kg of carbon and 13.1 kg of carbon released to the atmosphere via prestressed concrete and steel purlins respectively.

Table 3

Energy Breakdwn - Using Bio-Equivalent Units (MJ/Qtty)

Description	*Qtty*	*Biomass*	*Fossil fuel*	*Electricity*	*Imported*	*Total Energy (Bio-Eq)*	*Total Energy (TOE)*
Aggregates	1 m^3	0	178	0	0	178	99
Aluminium Extrusions	1 MT	0	17	55,881	233,100	288,998	147,477
Bricks	1000 Nos	8,528	86	0	0	8,614	8,576
Brickwork (9")	10 m^2	10,003	1,429	299	0	11,731	10,893
Cement	1 MT	0	6,625	1,869	0	8,494	4,282
Concrete (1:2:4)	1 m^3	0	2,649	598	0	3,247	1,664
Steel	1 MT	0	4,767	3,227	52,200	60,194	32,686
Timber Sections 3"x4"	1 m^3	0	577	3,364	0	3,941	1,403

WALLS

The energy inputs and carbon emissions corresponding to 10 m2 of 225 mm thick brickwork and 200 mm thick blockwork, both of which will have approximately similar strengths, are compared. The raw material requirement for 10 m2 of brickwork is 1173 nos. of bricks, 0.16 MT of cement and 0.59 m3 of sand. This is obtained from the Building Schedule of Rates (BSR) [11]. The raw material requirement for 10 m2 of blockwork is 120 Nos. of 200 mm x 200 mm x 400 mm cement blocks, 0.04 MT of cement and 0.18 m3 of sand. This is also obtained from the BSR [11].

The energy inputs corresponding to 10 m2 of brickwork and blockwork are 10.89 GJ and 0.95 GJ respectively in terms of TOE, indicating that brickwork is around 11 times more energy intensive than blockwork. However on the basis of bio-equivalent units the ratio is around 6. Net carbon emissions are similar, with 40.6 kg of carbon being released to the atmosphere via brickwork compared to 41.7 kg of carbon via blockwork.

ROOFS

The energy inputs and carbon emissions corresponding to a 10 m2 plan area of a calicut tile roof and an asbestos roof were compared. The raw material requirement for a calicut tile roof is 0.02 m3 of air-dry treated

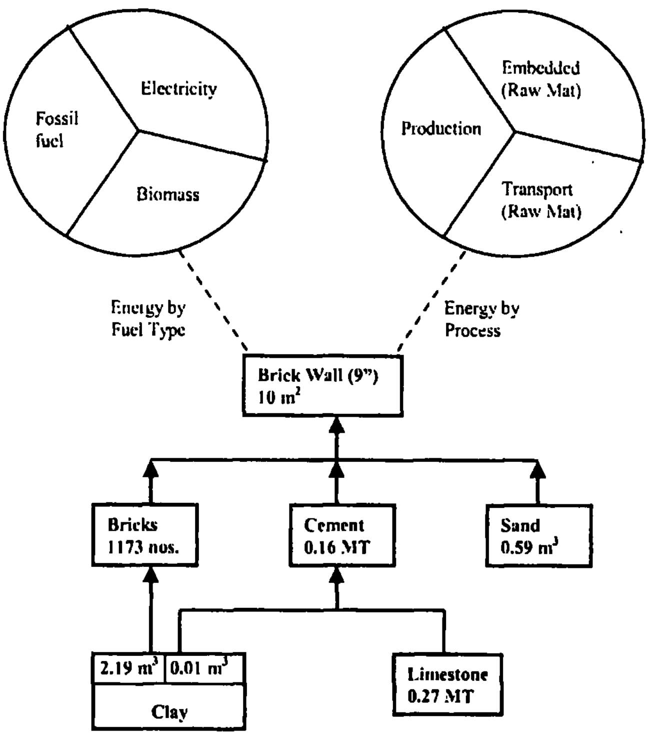

Figure 1: Hierarchical Arrangement of Materials for Brickwork

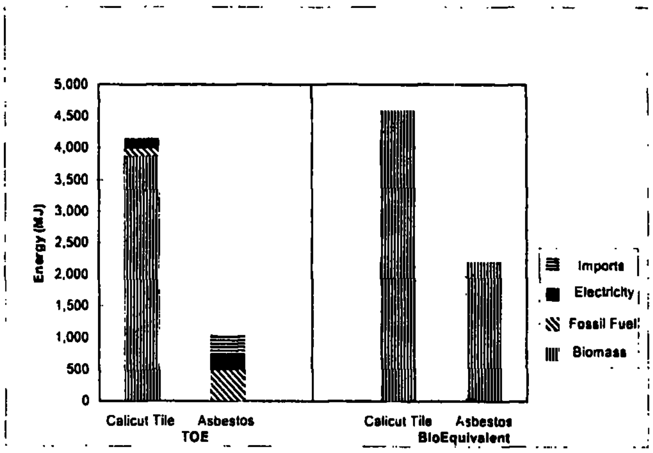

Figure 2: Embedded Energy Comparison for Roofs (10m²)

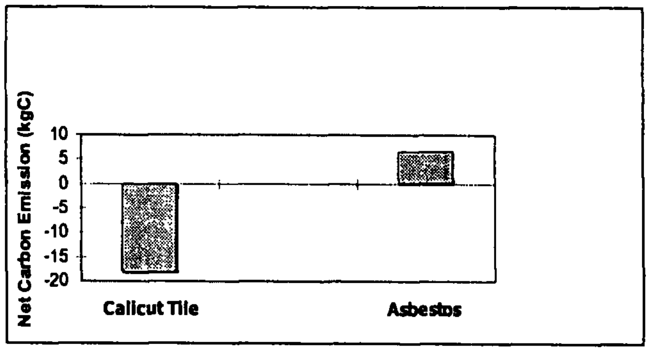

Figure 3: Carbon Emission Comparison for Roofs (10m²)

timber purlins, 0.06 m3 of air-dry treated timber planks (for the reepers) and 156 nos. of calicut tiles. These quantities are obtained from the BSR [11]. The raw material requirement for an asbestos roof is 0.11 m3 of air-dry treated timber purlins and 12.29 m2 of asbestos sheets. These requirements are also obtained from the BSR [11].

The energy inputs corresponding to a 10 m2 plan area of a calicut roof and an asbestos roof are 4.1 GJ and 0.75 GJ respectively in terms of TOE, indicating that the calicut tile roof is around 5 times more energy intensive than an asbestos roof. However on the basis of bio-equivalent units the ratio is only around 2. A comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 2. Figure 3 indicates that 18 kg of carbon is stored for the calicut tile roof compared to 6.5 kg of carbon released to the atmosphere via the asbestos roof.

WINDOWS

The energy inputs and carbon emissions corresponding to aluminium and timber windows of size 1250 mm x 1550 mm with two shutters were compared. The raw material required for an aluminium window is 15.7 kg of aluminium extrusions (7.96 kg for the frame and 7.74 kg for the shutter) and 1.9 m2 of 3 mm thick glazing. To construct a timber window one needs 0.04 m3 of rough purlins for the frame, 0.01 m3 of rough planks for the shutter, 1.5 m2 of wood painting and 1 m2 of 3 mm thick glazing.

The energy inputs corresponding to an aluminium window and a timber window of similar size are 2.44 GJ and 0.20 GJ respectively in terms of TOE, indicating that the aluminium window is around 12 times more energy intensive than the timber window. On the basis of bio-equivalent units the ratio is around 10. Furthermore, 11.2 kg of carbon is stored for the timber window compared to 50.3 kg of carbon released to the atmosphere via the aluminium window.

DISCUSSION

The analyses carried out indicate that, among the more common construction materials considered, the lowest energy option is timber. For example, on the basis of TOE, timber purlins are around 23 times less energy intensive than steel purlins and 4 times less energy intensive than prestressed concrete purlins. Similarly timber windows are around 12 times less energy intensive than aluminium windows. This is consistent with other research findings [6]. However, because of the world-wide phenomenon of deforestation, the use of timber will be possible only with aggressive re-forestation and perhaps even the use of biotechnology.

Wood products have negative carbon coefficients as well, i.e. they store more carbon than is emitted in their use for construction. For example, for purlins of 3 m span, 5.6 kg of carbon is stored for the timber purlin compared to 3.7 kg and 13.1 kg of carbon released to the atmosphere via prestressed concrete and steel purlins respectively. For windows of size 1250 mm x 1550 mm, 11.2 kg of carbon is stored for the timber window compared to 50.3 kg of carbon released to the atmosphere via the aluminium window.

It is also seen that materials which use wood fuels (e.g. bricks and tiles) consume more energy. However, the use of wood fuels is more competitive when compared on a bio-equivalent unit basis. For example, the energy input corresponding to a calicut tile roof and an asbestos roof, which have a similar plan area of 10 m2, is 4.1 GJ and 0.75 GJ respectively in terms of TOE, indicating that the calicut tile roof (where wood is the fuel used for the production of calicut tiles) is around 5 times more energy intensive than an asbestos roof; however on the basis of bio-equivalent units the ratio is only around 2 (see Figure 2). When the energy input corresponding to 10 m2 of brickwork and blockwork is considered, brickwork (where again wood fuels are used for the production of bricks) is around 11 times more energy intensive than blockwork; however on the basis of bio-equivalent units the ratio is only around half that value. Furthermore, with respect to carbon emissions, wood fuels are considered to be self-sustaining, as the carbon released during burning is that which has been absorbed from the atmosphere and stored. If wood fuels are to be promoted however, fuel wood farming would have to be undertaken on a large scale. The use of wood fuel would also decrease dependency on fossil fuels.

The variety of energy sources and the consequences of raw material extraction would also result in differing environmental costs. For example, blockwork is 11 times less energy intensive than similar strength brickwork. Although the mining and transporting of river sand, which is a major raw material for blocks, may have a rather low energy cost, thus resulting in a low embedded energy for cement blocks, the environmental cost of sand mining may be high, giving rise as it does to river bed degradation and coastal erosion [12]. Hence, future studies must account for a comprehensive environmental costing of building materials, using the techniques of environmental economics.

The question also arises as to whether the embedded energies of imported raw materials should be given importance when making decisions regarding the choice of building materials. For example though aluminium windows are around 12 times more energy intensive than timber windows, 88% of the total embedded energy in the former is of imports (i.e. aluminium billets). Hence, on the one hand, the use of aluminium windows may be considered acceptable or even desirable, because the energy expenditure is incurred overseas, and not nationally. On the other hand a continuing shortage of world energy sources and an increasing world demand for energy will increase the market price of energy, which in turn will be reflected in the increased price of imports. Thus eventually the embedded energy of imports too will play an important role in the choice of building materials.

GROSS EMBEDDED ENERGY IN BUILDINGS

SELECTION OF BUILDINGS

Building construction accounts for approximately 69% of the total activities carried out in the Sri Lankan construction sector [13]. According to the gross fixed capital formation by type and purchaser at constant (1990) prices, out of the total building construction carried out, approximately 64% is residential buildings [14].

Around 87% of the housing units in Sri Lanka consist of single houses with 58% having floor areas between 25-100 sq.m., and 16% having more than 100 sq.m. [15]. Therefore two houses were selected to represent each of the above ranges, i.e. a single storey house of floor area 49 m2 and a two storey one of floor area 120 m2. Around 50% of all housing units are constructed out of bricks and 16% out of cement blocks [15]. The most predominant types of roofing materials used in construction are calicut tiles and asbestos, jointly accounting for around 66% [15]. Therefore the two houses selected had the above materials for the walls and roofs (see Table 4). These were in fact type plan houses designed by the National Housing Development Authority (NHDA).

An office building of eight storeys with a total floor area of 3940 m2 was also studied, mainly to find the effect of air conditioning loading on the operational energy. The building was a reinforced concrete framed building with brick infill walls and supported on a reinforced concrete raft foundation.

COMPUTATION OF GROSS EMBEDDED ENERGY

There was insufficient data to find the Sri Lankan energy requirement for finishing work such as tiling, sanitary fittings, electrical installations etc. Thus gross energies for the embedded energies of the buildings were calculated by neglecting these items. Therefore the actual gross construction (or embedded) energy requirement will be higher than the calculated value; however other researchers have shown that the contribution from the above items are not that large [2].

Variations to the typical houses above were also studied, using different building materials to represent maximum and minimum energy intensive houses. These were compared in order to obtain a range for the embedded energy of a house. These high and low energy intensive construction material types are based on the comparisons made in the previous section (see Table 4). For the single storey house the gross embedded energy value was found to lie between 2.4 and 4.9 GJ/m2, and for the 2 storey house between 3.5 and 5.7 GJ/m2. For the air conditioned office building the actual gross energy was found to be 5.5 GJ/m2.

Table 4

Selection of a House

Type of Specification	Typical House Details Based on ref. 15	House Type A	House Type B
Floor Area	25-100 sq.m. - 58% > 100 sq.m. - 16%	120 sq.m.	49 sq.m.
Roof	Calicut tiles Or Asbestos - 66%	Asbestos	Calicut Tiles
Wall	Bricks - 50% Cabook or Cement Blocks - 16%	Cement Blocks	Bricks
Type of structure	Single House – 87%	Single House (2 storey)	Single House (1 storey)

A review of the literature revealed a very wide range in the gross embedded energy per unit floor area of a building calculated by different authors, even for the same building type. For residential construction, for example, the range was from about 1.2 to about 8 GJ per square metre [2]. It is seen that the embedded energies estimated in this study (i.e. between 2.4 and 5.7 GJ/m2) lie in the above range.

INFLUENCE OF BUILDING COMPONENTS ON EMBEDDED ENERGY

The contributions to the total embedded energy of the houses from various building elements made of minimum and maximum energy intensive materials (as defined in Table 4) was next determined. In the percentage ranges stated below, the first value corresponds to the contribution from the minimum energy material in the minimum energy house, while the second value corresponds to the contribution from the maximum energy material in the maximum energy house.

The influence from walls for the two storey house is 10% to 44%; for the single storey house it is 29% to 49%. This shows that the walls can contribute a significant proportion of the gross energy and that they have a wide range as well. This is because there is a large difference in energy contents between brick walls and block walls (as seen before). It also shows that choosing block walls instead of brick walls could make the greatest contribution to the reduction of gross embedded energy in residential buildings of 1-2 storeys. The influence from roofs for the two storey house is 4% to 7%, whereas it is 8% to 16% for the single storey house. It should be noted that this energy contribution from the roof is somewhat smaller than the corresponding cost contribution. The contribution from the floor slab for the two storey house was found to be around 7% [16], which is much lower that the cost contribution.

Although alternatives for plastering were not studied, the contribution from wall plastering is 29% to 13% for the single storey house and 32% to 17% for the two storey house; and that from the brick paved, cement rendered floor is 22% to 10% for the single storey house and 5% to 2% for the two storey house. This indicates that the elimination of plastering (if acceptable to house owners) can also contribute significantly towards reducing the embedded energy of houses. In this context unplastered block walls may be more acceptable than unplastered brick walls, because of the poor dimensional accuracy of Sri Lankan bricks.

OPERATIONAL ENERGY

An indication of the annual operating energy requirement of the typical houses that have been used in this research was obtained by a 1998/1999 sample survey of household energy consumption and shown in Table 5. The houses that were surveyed were those constructed according to the NHDA type plans used for taking off BOQ quantities. The operational energy requirement was of two types namely, (i) electrical energy required for the lighting and other electrical equipment and (ii) fuel used for cooking. Most of the houses surveyed made use of Liquid Petroleum Gas for cooking, and the contribution from this is around half the contribution from electricity consumption.

For the air-conditioned office building the annual operational energy was found to be 3706 GJ or 964 GJ/m2, based on an electricity consumption of 213,730 kWh over 4 months.

COMPARISON OF EMBEDDED AND OPERATIONAL ENERGY

The ratios between total embedded energy and annual operational energy for the above buildings are given in Table 5. For the houses, the embedded energies for minimum and maximum energy material options are also given, in addition to the actual values. It is seen that the

Table 5

Comparison of Embedded and Operational Energy

Type of Building	Construction Energy(Embedded) (GJ)			Annual Operational Energy (GJ)	Construction Energy/ Annual Operational Energy		
	High	Low	Actual		High	Low	Actual
House A (2 Storey)	581	313	325 (3.6 GJm^2)	16.5 (138 MJ/m^2)	35	19	20
House B (1 Storey)	231	107	220 (4.5 GJ/m^2)	8 (163 MJ/m^2)	29	14	28
Air Conditioned Office Building			17,424 (4.4 GJ/m^2)	3,706 (964 MJ/m^2)			5

above ratio ranges from 14 to 35 for the houses while for an office building with air-conditioning loading it is 5.

This shows the large influence that air-condition loading has on the operational energy. The operational energy of the air conditioned building (964 MJ/m2) is around 6 times higher than those for the houses (see Table 5).

Alhough air conditioning has a large contribution towards the annual operational energy of a building, the total number of air conditioned buildings are small for a developing country such as Sri Lanka. Nevertheless, the above results show that the focus of energy efficient design for buildings with air-conditioning has to be on the operational energy. On the other hand, for houses, which are largely not air conditioned, the way to promote energy efficiency is by reducing the embedded energy through the appropriate choice of building materials. This is borne out not only by the high ratios of construction to operational energy ratio obtained, but also by the fact that the ratios for the houses with low energy materials are around half those for the houses with high energy materials.

Figure 4 shows some comparative ratios between total embedded energy and annual operational energy. In the case of an air conditioned office building in Sri Lanka, this ratio (referred to as "Min" in Figure 4) is similar to the ratios obtained for houses in the U.K. and New Zealand (where operational energy includes space and water heating) [2]. However, for houses without air conditioning in Sri Lanka the above ratio (referred to as "Max" in Figure 4) is very much higher than those obtained in temperate zone countries.

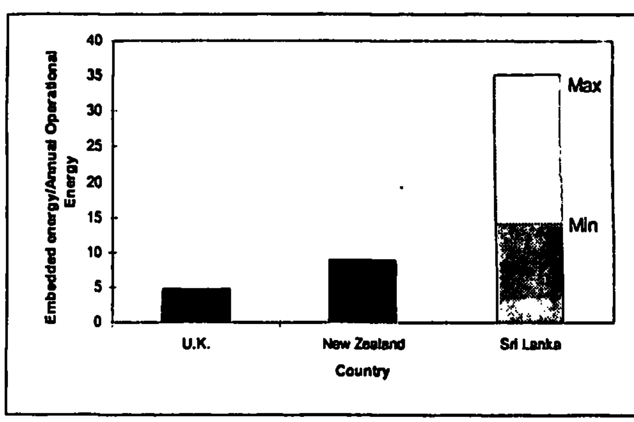

Figure 4: Comparison of Embedded and Operational Energy for Houses

CONCLUSIONS

1. The embedded energies and carbon coefficients obtained for building materials used in Sri Lanka are broadly consistent with the findings of other researchers for these materials. Embedded energies were also obtained on the basis of "bio-equivalent" units, where 1 GJ of electrical energy and 1 GJ of fossil fuel energy were considered equivalent to 5 GJ and 1.8 GJ respectively of biomass energy.

2. Among the more common construction materia c considered, the lowest energy option is timber while the highest is steel, with concrete in between. Timber products have negative carbon coefficients as well, i.e. they store more carbon than is emitted in their use for construction, while the carbon emissions from steel products will be greater than those from concrete products.

3. Materials which use wood fuels (e.g. bricks and tiles) consume more energy. However, the use of wood fuels is more competitive when compared on a bio-equivalent unit basis. Furthermore, with respect to carbon emissions, wood fuels are considered to be self-sustaining, as the carbon released during burning is that which has been absorbed from the atmosphere and stored.

4. The energy contribution from walls for a typical two storey house is 10% to 44%; for a single storey house it is 29% to 49%. The walls contribute a significant proportion of the gross energy and have a wide range as well. This indicates that choosing block walls instead of brick walls could make the greatest contribution to the reduction of gross embedded energy in residential buildings of 1-2 storeys. The contribution from wall plastering is 29% to 13% for the single storey house and 32% to 17% for the two storey house. Hence, the elimination of plastering (if acceptable to house owners) can also contribute significantly towards reducing the embedded energy of houses.

5. The ratio between total embedded energy and annual operational energy for the buildings selected ranges from 14 to 35 for the houses, while for an office building with air-conditioning loading it is 5. Hence, the focus of attention for energy efficient design should be on the operational phase for air-conditioned buildings. For houses in tropical countries however, which are generally not air-conditioned, energy efficiency is best achieved by the appropriate choice of construction materials.

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