EVALUATION OF THE EMBODIED ENERGY IN BUILDING MATERIALS AND RELATED CARBON DIOXIDE EMISSIONS IN SENEGAL

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Summary

The determination of the energy embodied in building materials and the related carbon dioxide emissions is a key aspect in the evaluation of buildings' performance. Few data about these factors are available in the technical literature, especially for the developing world. This paper alleviates this deficiency by proposing data for Senegal.

The methodology for embodied energy calculations is based on the well-known process analysis and includes the energy use associated with construction activities. The CO_2 emissions due to the production of building materials and on-site installation are estimated according to a methodology proposed by the International Panel on Climate Change. Water, three energy resources, eight building materials, and three envelope components are evaluated. The detailed estimation of embodied energy and CO_2 emissions for gravel is presented as an example.

It was initially expected that, owing to lower process efficiencies, the embodied energy of building materials produced in Senegal would be higher than those produced in industrialized countries. The comparison of Senegalese data with data available in the literature shows that this is not the case. Such a result is probably due to the fact that in developing countries in general, there is less automation in the manufacturing processes, and more human energy.

1. Introduction

Building projects should be designed and their performance evaluated based on their life-cycle energy use, life-cycle cost and life-cycle carbon dioxide emissions. The life cycle energy use (LCE) can be expressed as:

LCE = initial (or embodied) energy + n ·annual operating energy use, where n is the life duration of the building.

It is relatively easy to estimate the energy consumption and the related carbon dioxide emissions associated with the building operation. Much more difficult is the estimation of embodied energy and related carbon dioxide emissions in building materials; it requires information about the energy used throughout the entire manufacturing and installation process (Cornelissen 1998). Unfortunately, building designers do not have easy access to this information. The published values of specific embodied energy or energy content, expressed in MJ per kg of material or MJ per m^3 or MJ per m^2, vary quite significantly in some cases. For instance, in Canada, a study (SCHL 1991) gives a value of 0.078 MJ/kg for cement while a more recent database (ATHENA 1999) gives a value of 5.2 MJ/kg for the same product in the same country. The use of these values, without the appropriate interpretation, could lead to meaningless results. A further level of difficulty arises for developing countries since available specific embodied energy data have been developed from information collected in industrialized countries. So, is it accurate to use those data in the design of buildings in developing countries? This paper is a contribution to the topic, presenting the case of Senegal.

In Senegal, building materials fall into two categories: i) materials imported from industrialized countries and ii) materials produced in Senegal from raw materials. This paper presents the evaluation of the embodied energy and related carbon dioxide emissions of some materials, produced in Senegal, which are used for the construction of the exterior envelopes of commercial buildings (e.g., office buildings). This paper is part of a larger study (Ndiaye 2001) aimed at developing a decision tool to optimize building design at the early stage by simultaneously evaluating the life-cycle energy use, life-cycle cost and CO_2 emissions. A comparison is also made between data presented in this paper for Senegal and published data from industrialized countries in order to estimate the impact of factors such as technological differences or availability of energy resources.

2. Methodology

2.1 Energy Analysis

Energy analysis is the process of evaluation of the energy used, directly or indirectly, by a system to produce goods or services. The goal is to quantify the relantionship between human activities and these important resources that are non-renewable energy sources (Brown et al. 1996). Energy analysis does not examine directly the interaction of goods and services with the environment.

In the practice of energy analysis, a coefficient called the energy content (EC) or embodied energy of goods or services is expressed in MJ per unit (e.g., litre, kg, m^2, m^3, …); for instance 4 MJ/kg of gravel.

In order to harmonize the methods of evaluation of embodied energy in goods or services, the International Federation of Institutes for Advanced Study (Baird 1994; Alcorn 1998) recommended the use of several assumptions or guidelines. Some of them, relevant to the topic of this paper, are presented below:

- the human energy used in the production process is not taken into account, due to the high uncertainty associated with its evaluation;

- the evaluation of the energy content of goods or services should be performed using four levels of analysis. For level no.1, only the direct energy used should be considered, i.e. the energy directly used to produce goods or services. In level no.2, one should consider, in addition to the quantities evaluated in level no.1, the energy required by the production of inputs needed by the manufacturing process. Aside from the quantities associated with level no.2, the third level should consider the energy spent in the manufacturing process of equipment used to produce goods or services. The fourth level will necessitate the additional inclusion of the energy used to produce the equipment that was used to manufacture the equipment considered in the third level;

- the potential of products to be used as an energy source should be considered; for instance, some wood-based products can be used in combustion processes.

Three methods can be used for the calculation of the embodied energy of goods or services (Brown et al. 1996; Alcorn 1998): process analysis, input-output analysis, and hybrid analysis.

The most recent (at the time of the study) Senegalese input-output tables, developed in 1996 (DPS 1996), were not suitable for an input-output analysis due to their high degree of aggregation. The number of economic sectors considered in these tables is only 29, and all building materials are grouped in only one sector: the industry of building materials. In order to improve the quality of the data, the present study used the process analysis for the determination of embodied energy in building materials built in Senegal from raw materials.

2.2 CO_2 Emissions

The carbon dioxide (CO_2) emissions due to the production of building materials and on-site installation were estimated according to the methodology proposed by the International Panel on Climate Change (IPCC) (GIEC 2000). The six-step process includes (see Table 1): (1) the fuel consumption in original units, (2) the conversion to a common energy unit (GJ for example), (3) the determination of emission factors, (4) the multiplication of (2) by (3) to compute the carbon content, (5) the correction for the incomplete combustion, and (6) the conversion of carbon oxidized to CO_2 emissions. This methodology is suited to the present case since the oil and its derivatives are used as the primary energy source. The calculated CO_2-emission factor does not include other greenhouse gases such as carbon monoxide, methane, nitrous oxide and nitrogen oxide. In fact, as indicated by the IPCC (GIEC 2000), emissions of these latter depend on numerous factors: fuel type, operating conditions, combustion technology, control technology, age and maintenance of the equipment. All of these details were not available. Since the CO_2 emissions have the largest contribution to the overall greenhouse gas emissions, only those emissions were considered in this paper.

Table 1 Example of calculation of the CO_2-emission Factors for Gas-oil, Fuel-oil and Natural gas

Product	Fuel consumption (kg)	Energy equivalent (GJ/kg)	Emission (kgC/GJ)	Carbon content (kgC/kg)	Carbon oxidized (%)	Emission factor ($kgCO_2$/kg)
Gas-oil	1	0.04250	19.95	0.848	0.990	3.08
Fuel-oil	1	0.04151	21.10	0.876	0.990	3.18
Natural gas	1	0.05182	15.3	0.793	0.995	2.89

3. The Context of Senegal

The large majority of commercial buildings in Senegal are built of reinforced concrete that is used for columns, beams, and floors. The exterior walls are made of reinforced concrete or concrete blocks of 15 to 22 cm thickness, with a layer of cement mortar of 1.5 cm thickness on each side. Use of thermal insulation is rare; it is estimated that less than 2 % of all buildings are insulated (Diop et al. 1999). The use of single-glass windows is a common practice. Special types of glass for reducing solar heat gains are scarcely used due to a high initial cost.

In Senegal, energy sources are wood, charcoal, electricity and petroleum products. Wood and charcoal represent 60 % of the national energy balance. The remaining 40 % are divided between petroleum products (35 %) and electricity (5 %) (MEMI 1998). Electricity is almost entirely produced in thermal generating plants. The manufacturing sector essentially uses electricity or petroleum products (fuel-oil, gas-oil) as energy sources. Fuel oils are "hydrocarbon mixtures (liquid or liquefiable petroleum products) normally without any light boiling fractions for use in burners" (WEC 1992). Gas-oil (diesel-oil) designates a liquid hydrocarbon mixture for use in compression-ignition internal combustion engines (WEC 1992).

Following Cole (1999), consideration was given to the energy use associated with the following construction activities, which have been documented through numerous site visits:

1. The foreman uses a pick-up van provided by the company, and its contribution to the embodied energy is accounted for. Energy use for the transportation of workers and superintendent was not included in the analysis due to a lack of reliable data.

2. In the case of transportation of building materials, components and equipment (from the supply centres owned by the company), only the energy use for transporting sand and gravel from the sandpit or quarry was considered. All trucks use gas-oil. The concrete is prepared on site, and therefore no energy is used for its transportation.

3. Tractors are used to transport heavy equipment (concrete mixers, cranes, and dumpers). Tractors consume about 40 litres of gas-oil per 100 km.

4. All equipment on site use gas-oil directly (e.g., concrete mixer, dumpers, vibrators, blowpipes, and electricity generators) or indirectly, to generate electricity, in the case of cranes.

5. Support activities such as lighting, on-site office, and water supply. Fluorescent lamps are generally used between 19:00 and 07:00 hours. The site office holds a wet bar and is air-conditioned.

Data were collected from the Senegalese enterprises and the Statistics Bureau of Senegal. The following steps were undertaken (Alcorn et al. 1998):

- Each product is clearly identified, and its contribution to the building is quantified in terms of volume, mass or area. Properties such as density and specific heat are also recorded.

- The major actors (e.g., government, suppliers, service companies) are identified. The type and quantity of each product provided by each actor is recorded. The address and contact persons are noted down.

- The production processes are studied in detail. The corresponding inputs are identified.

- The direct and indirect energy consumption (the one used to produce the inputs to the process being studied) are quantified. The amount of energy use from various sources (e.g., coal, fuel oil, gas, electricity) was converted into the equivalent tons of oil.

- The corresponding prices of material and energy sources were recorded along with corresponding dates.

- Special consideration was given to the access to confidential data. Such information were recorded, however, there is an agreement of confidentiality that prevent the publication of some information.

4. Results

In the process of manufacturing building materials, the following resources are the most commonly used: electricity, water, fuel-oil, and gas-oil. Figure 1 shows the inter-relations between these four resources, based on the national average values (Thiam 2000). Crude oil is essentially imported. Fuel-oil and gas-oil are two of the products of its refining in Senegal. The inputs to the production and distribution of water are electricity, gas-oil (for water pumping), and chemical products for treatment.

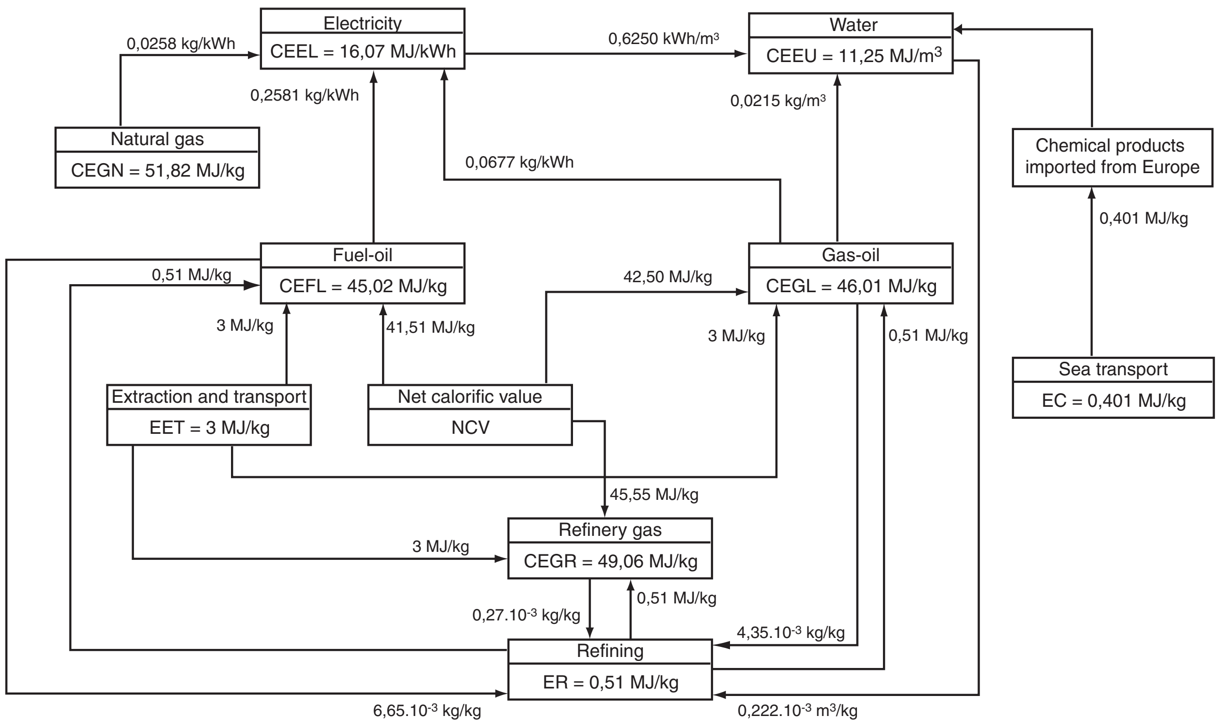

Figure 1 Inter-relations between the four resources: electricity, water, fuel-oil and gas-oil.

Since there is a strong interdependency between the unknown values, they are obtained from the simultaneous solution of the following system of six equations, in which the unknowns are written in bold.

$$\boldsymbol{ER} = QGLP \times \boldsymbol{CEGL} + QFLP \times \boldsymbol{CEFL} + QGRP \times \boldsymbol{CEGR} + QEUP \times \boldsymbol{CEEU} \tag{1}$$

$$\boldsymbol{CEEU} = QGLU \times \boldsymbol{CEGL} + QELU \times \boldsymbol{CEEL} + EDIV1 \tag{2}$$

$$\boldsymbol{CEEL} = QGLE \times \boldsymbol{CEGL} + QFLE \times \boldsymbol{CEFL} + QGNE \times CEGN \tag{3}$$

$$\boldsymbol{CEGL} = EET + NCV_{gas\text{-}oil} + \boldsymbol{ER} \tag{4}$$

$$\boldsymbol{CEFL} = EET + NCV_{fuel\text{-}oil} + \boldsymbol{ER} \tag{5}$$

$$\boldsymbol{CEGR} = EET + NCV_{ref\text{-}gas} + \boldsymbol{ER} \tag{6}$$

The following notations are used:

CE**	Embodied energy; in the case of electricity [CEEL] is given in (MJ/kWh); water [CEGL] in (MJ/m^3); fuel-oil [CEFL] in (MJ/kg) [FL]; gas-oil [CEGL] in (MJ/kg); natural gas [CEGN] in (MJ/kg); and refinery gas [CEGR] in (MJ/kg).
CETM	Embodied energy due to the transport by sea between Europe and Senegal (MJ/kg)
EDIV1	Energy of chemical products, evaluated for one m^3 of water (MJ/m^3)
EET	Energy used for the recovery and transport of crude oil to Senegal (MJ/kg)
ER	Energy used in the crude oil refining process (MJ/kg)

NCV Net Calorific Value (42.50 MJ/kg for gas-oil; 41.51 for fuel-oil; 45.55 for refinery gas)

**LU Amount of energy resource used in the production and distribution of each m^3 of water (QELU for electricity, QGLU for gas-oil)

Q**P Quantity of water used for the refining of each kg of crude oil (QEUP); amount of energy resource used for the refining of each kg of crude oil (QFLP for fuel-oil, QGLP for gas-oil, and QGRP for refinery gas).

Q**E Amount of energy resource used for the generation of one kWh of electricity (kg/kWh) (QFLE for fuel-oil, QGLE for gas-oil, and QGNE for natural gas).

The production of 1 kWh of electricity in Senegal requires on average: 67.73 g of gas-oil (QGLE = 0.0677 kg/kWh), 258.08 g of fuel-oil (QFLE = 0.2581 kg/kWh) and 25.84 g of natural gas (QGNE = 0.0258 kg/kWh).

Natural gas is extracted in Senegal. The energy used in its recovery and transport is assumed negligible relatively to its total energy content (the wells are of the flowing type and the extraction site is very close to the thermal plant). Consequently, the embodied energy of natural gas is equal to its net calorific value (NCV), i.e. CEGN = 51.82 MJ/kg.

The inputs to the production and distribution of water are: electricity and gas-oil (used for pumping), and chemical products for treatment. These chemical products are imported from Europe. The production and distribution of 1 m^3 of water requires: 0.625 kWh of electricity (QELU = 0.625 kWh/m^3), 21.48 g of gas-oil (QGLU = 0.0215 kg/m^3), and a quantity of chemical products corresponding to EDIV1 which is estimated to be equal to 0.222 MJ/m^3 (Ndiaye 2001).

In the recovery and transport of crude oil to Senegal (from Nigeria mainly), it is estimated that 3 MJ are used per kg. The following products are used to refine 1 kg of crude oil: 4.35 g of gas-oil (QGLP = 0.00435 kg/kg), 6.65 g of fuel-oil (QFLP = 0.00665 kg/kg), 0.27 g of refinery gas (QGRP = 0.00027 kg/kg), and 0.222 L of water (QEUP = 0.000222 m3/kg).

Given the above values, the solution of equations (1) to (6) is as follows:

CEEL = 16.07 MJ/kWh, embodied energy of electricity

CEEU = 11.25 MJ/m^3, embodied energy of water

CEFL = 45.02 MJ/kg, embodied energy of fuel-oil

CEGL = 46.01 MJ/kg, embodied energy of gas-oil

In addition, it was found that: the embodied energy of refinery gas CEGR = 49.06 MJ/kg, and the energy consumed in the refining of the crude oil ER = 0.51 MJ/kg.

The estimation of embodied energy (EE) and CO_2 emissions for gravel is presented as an example. Gravel is one of the components of concrete. In Senegal, it is obtained by crushing basalt, limestone, or sandstone. Basalt is exploited mainly in the Ndiack quarry (105 km from Dakar, capital of Senegal). Limestone and sandstone come from quarries that are closer to the capital.

Data presented in Table 2 were collected from a gravel production company. At the quarry, the company uses electricity generators and vehicles, both consuming gas-oil. The electricity consumption presented in Table 2 corresponds to the usage at the head-office situated in Dakar. The gas-oil consumption of trucks for the transportation of the gravel from the quarry to Dakar and back (unloaded) to the quarry, on a distance of 2 x 105 km is estimated at 108 MJ per ton of gravel. It is assumed that the transportation is done by 28 tons-load trucks consuming 36 litres of gas-oil every 100 km (Ecobalance 1999).

Table 2 Embodied Energy (EE) and CO_2-emission Factor for 1 Metric Ton of Gravel (Crushed Basalt)

Input	**Unit**	**Quantity**	**EE (MJ/Unit)**	**Total EE (MJ)**	**CO_2 ($kgCO_2$/Unit)**	**Total CO_2 ($kgCO_2$)**
Gas-oil	kg	1.128	46.01	51.90	3.08	3.47
Electricity	kWh	0.012	16.07	0.19	1.10	0.01
Transport to Dakar	unit	1	108.08	108.08	7.23	7.23
Water	m^3	0.008	11.25	0.09	0.75	0.01
Total by metric ton of gravel				**160.26**		**10.72**

Finally, the embodied energy of gravel is estimated at 160 MJ per ton, and the CO_2 emissions due to the production and transport of gravel at 10.7 kg per ton (this is the CO_2-emission factor of gravel).

Similar calculations were performed on several building materials produced and used in Senegal, using information from one production facility for each material. Data presented in this paper were obtained using an IFIAS level no.2 analysis. This limitation is due to the large amount of data required and extensive time required to collect additional information for level no.4 or no.3. Table 3 presents the summary of these calculations. More details on the various assumptions related to the calculations are found in (Ndiaye 2001).

Table 3 Embodied Energy (EE) and CO_2-emission Factors Estimated for Building Materials Produced and Used in Senegal. Comparison with Published Data

PRODUCT	UNIT	Senegal		Review of published data of EE (MJ/Unit) (Ndiaye 2001)			
		CO_2 (kg/Unit)	EE (MJ/Unit)	Number of values	Minimum value	Maximum value	Median value
Resources							
Gas-oil	Kg	3.08	46.01				
Fuel-oil	Kg	3.18	45.02	2	45.74	46.49	46.12
Electricity	KWh	1.10	16.07	9	9.88	11.67	10.60
Water	m^3	0.75	11.25				
Materials							
Concrete bar	kg	1.06	15.97	9	10.1	32	17.90
Sand (beach)	kg	0.004	0.06	3	0.04	0.10	0.05
Gravel	kg	0.01	0.16	4	0.051	0.3	0.12
Cement	kg	0.73	3.32	8	0.078	9.4	6.85
Cement block	unit	1.55	7.96	4	7.13	23.29	8.9
Mortar	m^3	298.06	1418.50	3	1682.43	5980	3200.00
Concrete	m^3	271.65	1403.55	13	1242	4600	2348.45
Reinforced concrete	m^3	476.96	4416.08	1	5040	5040	5040.00
Components							
Block wall	m^2	38.27	246.91				
Concrete wall	m^2	372.17	1973.98				
Slab (16 cm)	m^2	85.25	749.13				

5. Comparison of Embodied Data for Senegal with Published Data

Several sources of data about the embodied energy in building materials are available in the literature. Some examples are: Adalberth (1997), Alcorn (1998), ATHENA (1999), Baird (1994), Buchanan and Honey (1994), Friedman and Cammalleri (1995), Pierquet et al. (1998) and SCHL (1991). The units mostly used for presenting this information are: MJ/kg, MJ/m^3 and MJ/m^2. Major variations were observed among the values of embodied energy for the same product. For example, as stated in the introduction of this paper, the study released from SCHL (1991) determined an energy content of 0.078 (MJ/kg) for the cement produced in Canada. More recently, the study from ATHENA (1999) computed a mean value of 5.22 MJ/kg for the same product in Canada. The first study was an input-output analysis; the second one used a process analysis.

The comparison of published data on the embodied energy of selected building materials with those determined in this study for Senegal (Table 3) leads to the following observations:

- The embodied energy of all selected building materials produced in Senegal, except sand and gravel, is lower than the median values of data published in developed countries.

- The embodied energy of mortar and reinforced concrete produced in Senegal is below the minimum value of published data. For instance, in the case of mortar, the value calculated for Senegal is 1418 MJ/m^3, while the minimum published value is 1682 MJ/m^3 (ATHENA 1999). Since the composition of mortar is not indicated along with the published values, the difference may be due to its composition.

- It was initially expected that, due to lower process efficiencies, the embodied energy of building materials produced in Senegal would be higher than those of similar materials produced in industrialized countries. The results show that this is not the case. Such results could be explained by considering that in developing countries, in general, there is less automation in the manufacturing processes, and more human energy; however the latter is not taken into account in the analysis.

5. Conclusion

This paper presented original data about the embodied energy and related CO_2 emissions of some building materials produced in Senegal from raw materials. These data were calculated using a process analysis with data collected through site visits in Senegal. A methodology to obtain these data has been presented. Figure 1 is of particular interest as it shows the process analysis to obtain 1 kWh of electricity in Senegal. Table 3 summarises the results obtained for all building materials studied in this article and presents corresponding data for industrialized countries.

The comparison between embodied energy calculated for economic conditions of Senegal and those published in the industrialized countries revealed that, contrarily to what would be expected, there are only minor differences between these data. One can conclude that in developing countries the low energy efficiency of manufacturing processes is counterbalanced by the extensive use of human energy due to the relatively low level of automation.

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