Reduced embodied energy. Case analysis of a residential building in Lisbon, Portugal

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July 2018

Abstract

It is common that when talking about a building's life cycle energy, the only considered aspect is the operational energy. The part that is often left out is called the embodied energy of a building and represents the energy of manufacturing the construction materials and transporting them to the construction site (initial embodied energy), the energy required for the construction process, the energy required for the maintenance (recurring embodied energy) and the final disposal [1]. The objective of the present work is to quantify the embodied energy by developing a model and testing the application on a selected case as well as researching on sustainable solutions for demand reduction throughout the life cycle of the building. The case study selected is a single-family townhouse located in Belas Clube de Campo in Lisbon, Portugal. After the calculations, the results show that the embodied energy of the selected building represents 72% of the total life cycle energy and that some proposed solutions can possibly reduce it by 25% or more.

1. Introduction

Buildings account for 36% of the world final energy consumption and around 39% of the energy-related CO2 emissions. With this in mind, the built sector offers great potential for massive reductions in energy consumption and GHG emissions [2]. It is common that in building energy calculation methods the only energy consumption considered is the Operational Energy (OE). The OE is considered the energy consumed by the building during its lifetime after the construction phase until the end of life phase.

The EE can be defined differently during the life cycle of the building and has the following definitions:

- Initial Embodied Energy, which refers to the energy consumption both on and off site during the building process. The demand includes the extraction of raw materials, manufacturing and transportation.
- Recurring Embodied Energy, which refers to the energy demand for renovating and maintaining the building
- End of Life Embodied Energy, which refers to the energy demand of the final disposal [1]

2. Hypothesis and objective

The hypothesis is based on the fact that embodied energy is a crucial part of the life cycle of buildings and that it should be managed properly.

The objective is to quantify the embodied energy by developing a model and testing the application on a selected case as well as researching on sustainable solutions for demand reduction throughout the life cycle of the building

The embodied energy coefficients for different types of materials will be utilized for determining the manufacturing energy. In addition to this, the embodied energy for the transportation to the construction site will be assessed based on the origin of each material, and the embodied energy of the construction process itself.

The recurring embodied energy and the embodied energy for final disposal will not be assed.

3. Literature review

Embodied energy interpretations have a great variation as the available databases suffer from big incompatibilities. Due to the differences in parameters, the values for embodied energy greatly vary from study to study. [3]

In the analysis presented in the paper by (Zabalza, 2010 [4]) the variation of the embodied energy weight can be seen in different case studies. In sixty studies from nine different countries including Sweden, Germany, Australia, Canada and Japan the proportion of embodied energy varies between 9% and 46% of the overall life cycle energy when analyzing low energy buildings and between 2% and 38% in conventional buildings when considering a lifetime of 50 years

In the paper of (Chen 2001 [5]) the embodied energy analysis done concluded that steel has the highest impact among all the materials. This is exemplified in Figure 1:

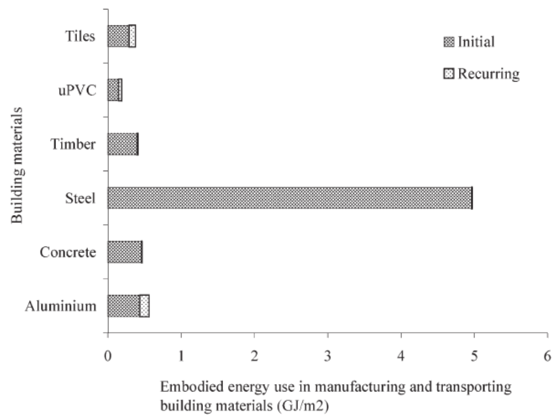

Figure 1. Embodied energy of different materials in the case study of (Chen 2001 [5])

It is mentioned that steel, together with aluminum account for 77 % of the total embodied energy.

Another embodied energy study for a normal 3-bed room semi-detached house in Scotland was done in the paper of (Asif 2005 [6]). It is interesting to mention that in this study, steel in not considered, and the biggest embodied energy content is given by concrete (Figure 2)

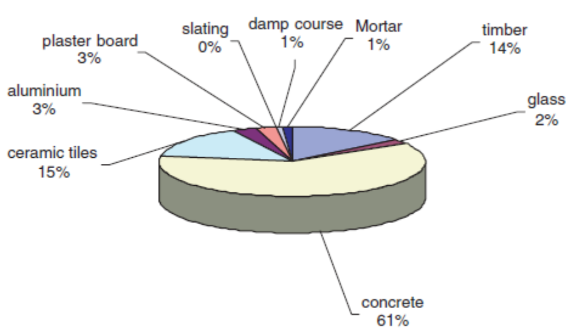

Figure 2 Embodied energy percentages in a case study building in Scotland [6]

In the paper of (Treloar 1998 [7]), it is hypothesizes that the top nine materials categories account for 90% of the total embodied energy of a building. These categories are iron and steel, concrete slurry, basic non-ferrous metals, mining products, plastic products, glass products, textile products, plaster and ceramics.

The findings in (Treloar 1998 [7]) confirm the other two mentioned studies of (Asif 2005 [6]) and (Chen 2001 [5]) with all three of them regarding steel and concrete products as the being the most energy demanding material categories in a building.

In the paper of (King 2004 [8]), the embodied energy analysis done concluded with a value of 7.83 GJ / m^2. They also highlight the fact that the result is on par with several case studies from the literature review that was done.

As it can be seen, results and conclusion vary from case to case, but similarities can be found through all the literature studies. Some of the results will be used to verify the accuracy of the present paper outcomes.

4. Model construction methodology

The embodied energy calculation model is using as a starting point the Bath University Inventory of Carbon and Energy (ICE) version 2.0. This inventory provides a comprehensive list of materials and their associated embodied energy expressed in [MJ/kg]. The energy for the materials transportation to the construction site and the energy required for the construction process are not included, so these need to be calculated separately.

For the transportation embodied energy, considering that the selected case study is from Portugal, with the assumption that all materials are transported to the construction site by either truck or sea, the values used as reference will be 2.5 [MJ/ton/km] for truck transportation and 0.7 [MJ/ton/km] for sea transportation. [9]

Another important aspect that needs to be included in the embodied energy analysis is the construction process itself, with primary focus on the land preparations.

During this stage the following construction processes have taken place (Table 1):

Table 1. Construction process for site preparation

Construction Process
Excavations of soils up to 0.30 m
Compaction of land
Transport to dump of products resulting from excavations
Excavation of foundation elements
Compaction of land
Transport to the dump of products resulting from excavation

It will be assumed that for the operations stated above the following machines were required:

- One hydraulic excavator
- One soil compactor
- One dump truck

It will be assumed that the excavator and the compactor can process up to 250 m^3 of soil per working day [10] while the dump truck capacity is approximately 10 m^3 per load [11].

The fuel consumption for the excavator and the compactor will be assumed as 17.29 liters/hour and for the dump truck 18.67 liters/hour [12].

The final embodied energy value will be the sum of the materials embodied energy (cradle-to-gate), the embodied energy of the materials transportation and the embodied energy of the construction process.

5. Case study analysis

The selected case study for the analysis of the embodied energy is the residential complex Belas Clube Campo – Lisbon Green Valley (Figure 3) located in the northern part of the Lisbon city in Portugal.

Figure 3Lisbon Green Valley [13]

The housing concepts put to offer are of two kinds: apartments and townhouses. The apartments are with 1,2 or 3 bedrooms with garage area and storage area. The townhouses are of two models: houses with 4 bedrooms and an office and houses with three suites and an office. All the townhouses come with a garage in the basement, swimming pool and garden.

From the housing concepts offered in Belas, the focus will be on the townhouse situated in Lot 307 (Figure 4). The house is currently in the operational phase and it has been evaluated by the LiderA certification system as being a class A+ building due to its high performances in energy management and good environmental and sustainable practices. [13]

Figure 4 Lot 307 Townhouse [13]

The building on lot 307 is a semi-detached house with a T5 typology for single family use with three floors and a total area of 449.00 m^2.

On the floor 0, the living room is facing west with a big opening to the terrace and swimming pool. The terrace is protected by the upper floors volumes. (Figure 5)

Figure 5 Townhouse 307 overview of terrace and swimming pool

The entrance hall is shared between the kitchen, living room (Figure 6), toilet, office and stairs access to the first floor and the basement.

Figure 6 Townhouse 307 Livingroom

On floor 1, two suites, two bedrooms and a toilet are present, while floor -1 incorporates a big parking garage, storage space and technical area.

From a renewable generation point of view, the townhouse has installed 2 “Vulcano FKC 2W” solar panels for domestic hot water production. For electricity production, 13 solar photovoltaic panels “Genius 4BB 250W” (Figure 7)are also installed on the roof and work together with a battery for energy storage with a 6 kW capacity.

Figure 7 Townhouse 307 renewable energy installation

In the global environmental performance, the townhouse on lot 307 was evaluated as exceptional A+ performance, obtaining 65.5 % improvements compared to common practices. [13]

6. Results and discussions

A total number of 117 identified materials have been analyzed from a cradle to gate perspective utilizing the ICE database and from a transportation embodied energy perspective.

In order to make the results more understandable, the materials have been divided into categories as follows:

- Steel
- Aluminum
- Iron
- Concrete
- Lightweight concrete
- Cement based materials
- Bitumen based materials
- Plastics
- Insulation
- Glass
- Stone
- Ceramics
- Gypsum
- Wood
- Resins
- Sand
- Zinc
- Windows PVC
- Windows Aluminum
- Power generation equipment
- Miscellaneous

The cradle-to-gate values offered in the ICE database are expressed in [MJ/kg], while the materials in the above list were expressed in various units of measurement. In order to easily estimate the energy embodied in each material, a series of calculations and assumptions were made as to match the lot 307 materials with the ICE database

One example for this process is the 6 cm cork insulation boards which were given in the list by their total area they cover of 78.41 m^2.

In order to determine their total mass in kilograms, the board's area, volume and density had to be researched. For this particular material, the total mass has been identified as being 940.92 kg.

The process is repeated for most of the materials, and the total value of embodied energy, incorporating both the cradle-to-gate value and the energy for transportation, has been calculated to be 3332.67 GJ.

Considering provided values for the construction process steps previously described in chapter 4, the total embodied energy has been calculated to be 45.88 GJ.

By summing up the above mentioned values, the total embodied energy for the townhouse 307 is 3378.55 GJ or 7.52 GJ/m^2. Referring to the paper from (King 2004 [8]), in which the value proposed was 7.83 GJ/m^2, the present work analysis is on par with the case studies from the literature.

Steel and concrete are the dominant categories in terms of embodied energy. Steel materials account for 18.31 % of the total embodied energy, while the concrete and lightweight concrete account for 14.61 % and 19.42 % respectively. The three categories account together for more than half of the total embodied energy with a percentage of 52.34%

By comparing the calculated embodied energy of the townhouse with its operational energy, a big difference will be observed. The total operational energy for an assumed lifetime of 70 years is 0.355 GWh, while the total calculated embodied energy value is 0.945 GWh accounting for 72 % of the life cycle energy.

The very big disproportion between the operational and embodied energy is caused by the design thinking towards a very efficient building. The townhouse 307 is a low energy building which can even achieve self-sustainment, and as mentioned in most of the literature analyzed, this increases the material use and automatically the embodied energy

The hypothesis mentioned in the beginning that the embodied energy is a crucial part of the life cycle energy of a building is confirmed based on the above mentioned results. As well, the need for reduction solutions is evident.

In this context, two possible reduction solutions have been analyzed:

- Utilization of 100% local materials
- Substitution of energy demanding materials

In the first scenario, by substituting the transportation distance of the imported materials with the transportation distance of local materials, an embodied energy reduction of 9.82 % is possible. The reduction potential is not very high for this specific case study because most of the materials used are of national origin.

In the second scenario, by substituting energy demanding materials like steel rods, concrete, polyethylene film, EPS boards and ceramic tiles with less energy demanding substitutes, a reduction potential of up to 25% is possible. It is important to notice that not all replacement possibilities have been calculated so this potential could be even higher.

As well it has to be mentioned that no economic feasibility study has been done and it was considered out of the scope of this project.

An estimation has been made in regards to the embodied carbon of the building as well and the results show that the total embodied carbon of materials is approximately between 150-200 tonsCO2-eq. As expected, the biggest amounts remained the same as for the embodied energy for the steel, concrete and lightweight concrete.

The final outcome of the work, after all the values and calculations have been explained, is the fact that embodied energy is a vital part of life cycle energy and should be carefully analyzed prior to any construction project.

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