Life cycle energy assessment and carbon dioxide emissions of wall systems for rural houses

Avaliação de ciclo de vida energético e de emissões de CO_2 em sistemas de vedação para residências rurais

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Abstract

Wall systems have a wide range of embodied energy due to the diversity of materials available. This paper analyzes the expenditure of energy and carbon dioxide emissions in internal and external wall systems (IEWS) of a rural residence of social interest in Cascavel, state of Paraná, Brazil. The methodology proposed by NBR ISO 14040 was used to perform a life-cycle energy assessment (LCEA) and the carbon dioxide emissions assessment ($LCCO_2A$) of these systems. Four scenarios were considered: reinforced concrete structure and ceramic blocks wall system, load-bearing masonry with concrete blocks, steel framing and reinforced concrete walls molded on site. As a result, it was found that it is possible to reduce energy consumption up to 25% by opting for reinforced concrete walls molded on site. In regards to CO_2 emission, it was verified that the difference is even greater, being able to reduce emissions by almost 32% when opting for this same scenario.

Keywords: Building materials. Embodied energy. Sustainability.

Resumo

Os sistemas de vedação têm uma ampla dispersão no valor energia incorporada devido à diversidade de materiais disponíveis. Este trabalho analisa o fluxo de energia e emissões de dióxido de carbono em sistemas de vedação vertical internas e externas (SVVIEs) de uma residência rural de interesse social localizada na cidade de Cascavel, estado do Paraná, Brasil. A metodologia proposta pela NBR ISO 14040 foi utilizada para realizar uma avaliação do ciclo de vida energético (ACVE) e a avaliação das emissões de dióxido de carbono (ACVCO$_2$*) desses sistemas. Foram considerados quatro cenários: estrutura de concreto armado com vedação de blocos cerâmicos, alvenaria estrutural com blocos de concreto, steel framing e paredes de concreto armado moldadas no local. Como resultado, constatou-se que é possível reduzir o consumo de energia em até 25%, optando pelas paredes de concreto armado moldadas in loco. Em relação à emissão de CO_2, verificou-se que a diferença é ainda maior, é possível reduzir as emissões em quase 32%, utilizando este mesmo cenário.*

Palavras-chave*: Materiais de construção. Energia incorporada. Sustentabilidade.*

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Recebido em 14/06/19
Aceito em 04/08/20

BRUNETTA, R. F. da S.; SOUZA, S. N. M. de; KORMANN, A. C. M; LEITE, A. H. Life cycle energy assessment and carbon dioxide emissions of wall systems for rural houses. **Ambiente Construído**, Porto Alegre, v. 21, n. 1, p. 37-50, jan./mar. 2021.
ISSN 1678-8621 Associação Nacional de Tecnologia do Ambiente Construído.
http://dx.doi.org/10.1590/s1678-86212021000100492

Introduction

Life Cycle Assessment (LCA) is an efficient tool for reducing energy consumption and greenhouse gas emissions in buildings. The LCA is a way of systematically evaluating the environmental impacts of a product or a process throughout its lifecycle and aims to reconcile the preservation of natural resources, take preventive actions regarding pollution, improve the economic system and also maintain a sustainable ecosystem (CIAMBRONE, 1997).

Different approaches can be adopted in the LCA; in this study, two approaches were adopted: life cycle energy assessment (LCEA) and life cycle carbon emissions assessment (LCCO$_2$A). The system analyzed includes manufacturing, maintenance, and the demolition phase of wall systems. Through the integrating LCA methods the inputs or processes that most affect sustainability can be identified, and also if these inputs are improved and environmental sustainability can be achieved more quickly (PHILLIS; KOUIKOGLOU; VERDUGO, 2017; ATMACA; ATMACA, 2015).

Sustainability assessment on walls has been carried out by other authors (LOTTEAU *et al.*, 2015; LEOTO; LIZARRALDE, 2019; MONTEIRO; FREIRE, 2012). However, these tools should be used individually so we are able to adopt the most appropriate strategy for each building (LEOTO; LIZARRALDE, 2019; REZAEI; BULLE; LESAGE, 2019). The greatest energy reduction potential incorporated in the Brazilian social interest buildings is connected to wall systems through the choice of materials and systems with less energy incorporated and greater durability, in order to reduce the necessity of maintenance and replacement of material (PAULSEN; SPOSTO, 2014).

The objective of this study is to identify which scenario requires the most energy and which scenario results in the greatest CO$_2$ emissions. The findings might open up strategies for future designs more sustainable. Based on our search in the literature, this paper presents the first study in the literature about LCEA and LCCO$_2$A of four wall systems in tropical countries. This research is also distinguished by the use of exclusively Brazilian embedded energy values and CO$_2$ emissions rates.

Method

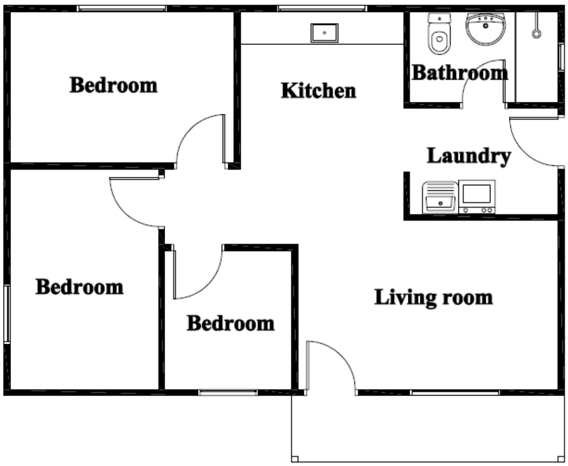
The projects analysed

The project selected for this study was the Rural 63 model of 63.86 m² of the National Rural Housing Program – NRHP. This model was selected because it is the most frequent in rural housing complexes. Figure 1 shows a sketch of this building model.

This program aimed to build 10,000 rural houses, in different regions of Brazil. This way, common construction techniques of housing estates in the city of study were selected.

Three IEWS were used as alternatives for the conventional structural system of reinforced concrete with ceramic block wall and the projects of the respective IEWS were elaborated according to the current regulations.

Figure 1 - **Sketch of the selected project**



Source: Empresa Paranaense de Assistência Técnica e Extensão Rural (2017).

Table 1 describes the scenarios analyzed. These construction systems were selected because these are the techniques most used by builders in the region.

Despite scenario 3 requiring a replacement of materials and qualified labor, we decided to analyze the steel frame as a constructive methodology, due to its agility, high level of quality and low waste generation (DUARTE; DALTRO, 2018). Campos (2014) reports that, due to the housing deficit in Brazil, faster construction methods, such as the steel frame, should be adopted. Duarte and Daltro (2018) present residential buildings built with steel frames constructed in areas of social vulnerability in Brazil and claim that very few studies have been carried out on the implementation of this technique with in this context. For example, Caldas *et al.* (2017) and Ramos (2019). In addition, once it is a rural area, rapid construction is preferable due to the need for labor displacement.

In order to survey the material quantities and services, the analytical compositions of National System of Research of Costs and Indices of the Civil Construction and Composition price table were used, which already consider the waste of material, labor and construction tools and equipment (CAIXA, 2007; TABELA…, 2008).

Methodology to analyze the life cycle of the IEWS

The research focuses on a IEWSs LCA of a rural house, which for the case study is located in the city of Cascavel, state of Paraná, Brazil. The building is located ten kilometers from the urban perimeter, on the margin of BR 369 highway, at latitude: S 24º 51' 52" longitude: W 53º 20' 18 ", at an altitude of 781 meters. According to NBR 15220-3, this region is located in bioclimatic zone 3, which requires the use of light outer walls reflecting solar radiation, cross ventilation and light thermal inertia materials (ABNT, 2005).

Following the definitions of NBR ISO 14040 incorporated energy and CO_2 emissions were considered as the product of this system (ABNT, 2009). As a function, there are the IEWS and as a functional unit the energy incorporated per square meter of construction (GJ/m² of construction) and CO_2 emissions to these systems per square meter of the wall (kg.CO_2/m² of the wall) because these are the most used units.

In order to elaborate the evaluation of the IEWS life cycle, we used the cradle-to-grave approach as already used by several authors (CABEZA *et al.*, 2014; ATMACA; ATMACA, 2015; INGRAO *et al.*, 2016; FILIMONAU *et al*., 2011; MUÑOS; MORALES; LETELIER, 2017). Figure 2 shows what was considered in each phase. Transport occurred from the extraction of the raw material to the deposition of the demolition material.

The pre-use phase consists of the procedures prior to the occupation of the residence. The use phase comprises the useful life of the residence. The post-use phase designates the period after the end of the useful life of the house.

Expenditure on energy and CO_2 emissions with water and other building systems were not computed. CO_2 emissions generated by the carbonation process that may occur in the structure were also not accounted. The life cycle duration considered in this work is 50 years, as recommended by the NBR 15575-1 (ABNT, 2013).

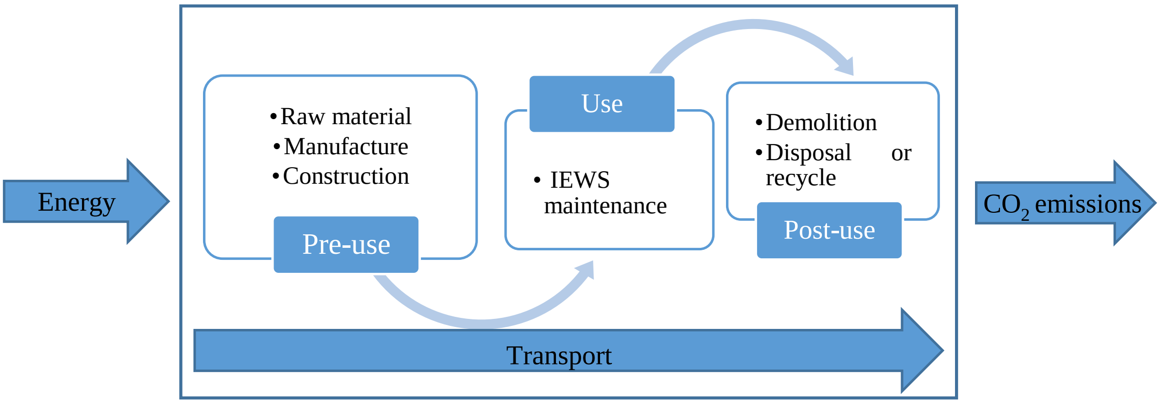
Energy and CO_2 emissions into material, with use of equipment and labor

In order to collect the energy incorporated into the materials, which are used in the pre-use and usage phase, a research was carried out in national studies, since the extraction, processing or manufacturing methods of each country have energy efficiency.

Table 1 - **Description of the scenarios**

Scenarios	Description
S1	Reinforced concrete structure, ceramic blocks wall system (9X14X19cm) and plaster.
S2	Load-bearing masonry with concrete blocks (14X19X39cm) and plaster.
S3	Steel frame composed of external OSB board seal (18 mm), rock wool (50 mm) fill and internal wall made with gypsum board (12.5 mm).
S4	Reinforced concrete walls on site with a thickness of 20 cm (Fck = 20 MPa).

Figure 2 - **IEWS LCA system considered in accordance with ISO 14040**



The incorporated energy used for each material was the average of the values found in the national literature. Values that would cause the average to have a coefficient of variation greater than 100% were excluded. CO_2 emissions are directly linked to energy consumption, so an inventory with CO_2 emission factors (from energy costs) per kilo of the material was developed.

The most relevant studies in the national literature were consulted to compose the inventory of this research. The selected works were:

(a) [1] Brazil (1982);

(b) [2] Guimarães (1985);

(c) [3] Carvalho (2002);

(d) [4] Sposto (2004);

(e) [5] Soares and Pereira (2004);

(f) [6] Tavares (2007);

(g) [7] Stachera Junior and Casagrande Junior (2007);

(h) [8] Lobo (2010);

(i) [9] Graf (2011);

(j) [10] Nabut Neto (2011);

(k) [11] Costa (2012);

(l) [12] Carminatti Junior (2012);

(m) [13] Taborianski and Prado (2012);

(n) [13] Silva (2013);

(o) [14] Souza (2013);

(p) [15] Falcão (2013);

(q) [16] Silva and Silva (2015); and

(r) [17] Pedroso (2015).

Table 2 shows the average of the values of embodied energy and CO_2 emissions found in the literature.

Some services require equipment (such as an immersion vibrator and drill). In this case, the power of the equipment and the number of hours of use were obtained from the SINAPI spreadsheets. The energy for the use of equipment was calculated from this information in all the analyzed phases. The electrical energy conversion factor for CO_2 emissions used was 0.038 kg.CO_2/MJ (EMPRESA…, 2017).

Energy spent by labor was calculated using the conversion factor proposed by Bouchard *et al*. (1983) and the number of working hours calculated from the SINAPI spreadsheets.

Table 2 - **Embodied energy and CO_2 emissions considered**

Type of building material	Embodied energy (MJ/Kg)	References	CO_2 emissions ($kgCO_2/kg$)	References
Scenario 1				
Ceramics (blocks)	3.37	[1][2][4][6][8][10][17]	0.4	[5][7][11][13][17]
Gravel	0,15	[6][8]	-	-
Hydrated lime	3.3	[1][2][8][12][14][17]	0.94	[5][11][13][14][17]
Paint color	51.12	[6][8][12]	1.64	[11]
Portland Cement	3.57	[1][2][6][8][10][12][14][17]	0.63	[3][5][11][13][14][17]
PVC ^{II} (spacers)	50.41	[6][14][17]	0.45	[11][17]
Release agent	86.13	[9]	-	-
Sand	0.05	[1][2][6][8][12][15][16]	0.01	[5][11][15]
Spackling paste	117.84	[8]	-	-
Steel	21.92	[1][2][6][17]	1.61	[5][11][17]
Wood (air-dried)	0.5	[6]	0.04	[17]
Scenario 2				
Gravel	0.15	[6][8]	-	-
Hydrated lime	3.3	[1][2][8][12][14][17]	0.94	[5][11][13][14][17]
Paint color	51.12	[6][8][12]	1.64	[11]
Portland cement	3.57	[1][2][6][8][10][12][14][17]	0.63	[3][5][11][13][14][17]
Sand	0.05	[1][2][6][8][12][15][16]	0.01	[5][11][15]
Spackling paste	117.84	[8]	-	-
Steel	21.92	[1][2][6][17]	1.61	[5][11][17]
Scenario 3				
Cement board	3.03	[1][2][6][9]	0.16	[11]
OBS ^{I} board	7.5	[6]	0.34	[11]
Paint color	51.12	[6][8][12]	1.64	[11]
Plaster board	5.03	[6][8][9]	0.45	[11][13]
Rockwool	19	[6]	0.69	[13]
Steel profile	32.70	[6][10][9]	1.61	[5][11][17]
Scenario 4				
Aluminum	152.94	[18]	3.6	[11][13]
Gravel	0.15	[6][8]	-	-
Paint color	51.12	[6][8][12]	1.64	[11]
Portland cement	3.57	[1][2][6][8][10][12][14][17]	0.63	[3][5][11][13][14][17]
PVC ^{II} (spacers)	50.41	[6][14][17]	0.45	[11][17]
Recycled aluminum	17.3	[6]	-	-
Release agent	86.13	[8]	-	-
Sand	0.05	[1][2][6][8][12][15][16]	0.01	[5][11][15]
Spackling paste	117.84	[8]	-	-
Steel	21.92	[1][2][6][17]	1.61	[5][11][17]

Note: ^{I}Oriented Strand Board;
^{II}Polyvinyl Chloride; and
^{III}Conversion factors for estimating CO_2 emissions of some materials were not found in the literature, and therefore, were not considered in this study. In Table 2, these values were replaced by a hyphen (-).

Energy and CO_2 emissions coming from transport

At all stages of the life cycle of IEWS there are energy costs and emissions arising from the need to transport materials, waste and workers. Thus, energy spent with materials and waste transport was estimated according to the distance between the point of extraction or manufacturing and commercialization, and between the point of sale and use. The energy consumption was calculated using the load capacity and average consumption from Refs. Ministry of the Environment (2014) and Energy Research Company (2017). The value of 1.44 MJ/ton/km was considered for light vehicles and 0.69 MJ/ton/km for medium trucks. The CO_2 emission factors used to compute emissions with transport considered refers to 2.681 $kg.CO_2/L$ of diesel oil (GHG PROTOCOL, 2017).

Energy and CO2 emissions from the use phase

To obtain the maintenance energy, Equation 1 was used; it estimates the energy of replacement of each material (RAMESH; PRAKASH; SHUKLA, 2010).

$$ME = EI \times Mi\,[(LB/LM) - 1] \qquad \text{Eq. 1}$$

Where:

ME is the maintenance energy;

EI is the content of energy of the material (i) per unit;

Mi is the amount of building material (i);

LB is the life span of the building; and

LM is the and life span of the material (i).

LB considered is 50 years (ABNT, 2003). LM average for indoor painting is 3.5 years and for outdoor painting is 10 years (ABNT, 2013). In addition to painting, steel framing walls require replacement of some materials, the cementitious plates must be replaced in 40 years and OSB sheets and gypsum plates in 30 years (PALÁCIO, 2013).

To evaluate CO_2 emissions in the use phase, the emission factors per kilogram of material multiplied by the amount of spare materials were used (this factors were showed in Table 2).

In this phase, the energy spent on labor was calculated as proposed by Bouchard *et al.* (1983)

Energy and CO2 emissions from the post-use phase

To obtain the energy in the demolition or deconstruction phase and to determine the CO_2 emissions with demolition or deconstruction, the factors indicated by Caldas (2016) based in Brazilian experience, which include the use of equipment and labor, were utilized.

Energy and CO_2 emissions resulting from transporting waste from the construction site to the material disposal site were accounted in the same way as in the pre-use and use phase.

Results and discussion

Energy incorporated into IEWS

By analyzing

Figure 3 shows that S4 requires a considerably larger amount than the other scenarios in the pre-use phase, which includes extraction, fabrication or processing, transportation, human labor and equipment use in the construction of the IEWS, this behavior is due to the high energy value incorporated into the aluminum frames.

However, there is the possibility of multiple uses of the same forms when there is a repetition of the same model of housing unit, taking into account that the case study project is a housing of social interest and it is known that this type of building is replicated several times. Thus, a reduction of the energy of the pre-use phase with the reutilization of the aluminum forms is observed, according to Figure 3.

Pedroso (2015) in his research on energy incorporated into IEWS in a case study for the Federal District obtained 2.02 GJ/m² of energy in the pre-use phase for a scenario similar to S1 of this work. As for load-bearing masonry with concrete blocks (wall system similar to S2) the same author found the value of 1.21 GJ/m² while in this work the value reached was 1.94 GJ/m². These differences can be explained by the energy spent with transport, the distances between extraction point and manufacturing to construction are different depending on the location of the case study.

Figure 4 shows the pre-use energy for scenario S4 for several numbers of reuse. A reduction of the pre-use energy with 100 reuses is observed, but from 500 reuses to 1000 there are no significant reductions. Comparing with the pre-use energy of the other scenarios it is noticed that with 100 repetitions S4 already becomes more efficient than the others. For this study, 100 reuses of aluminum formwork was adopted, although it is possible to reuse it more often, however, rural housing condominiums rarely exceed 100 homes.

Figure 3 - **Pre-use energy of each scenario**

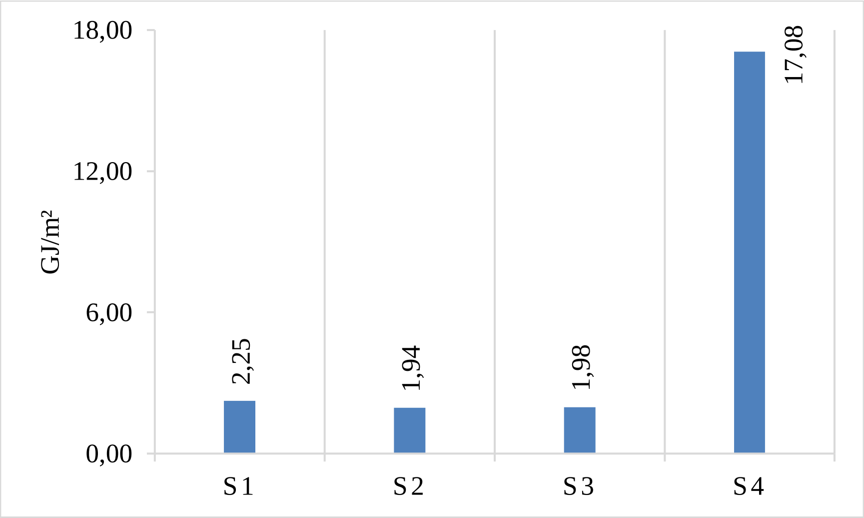
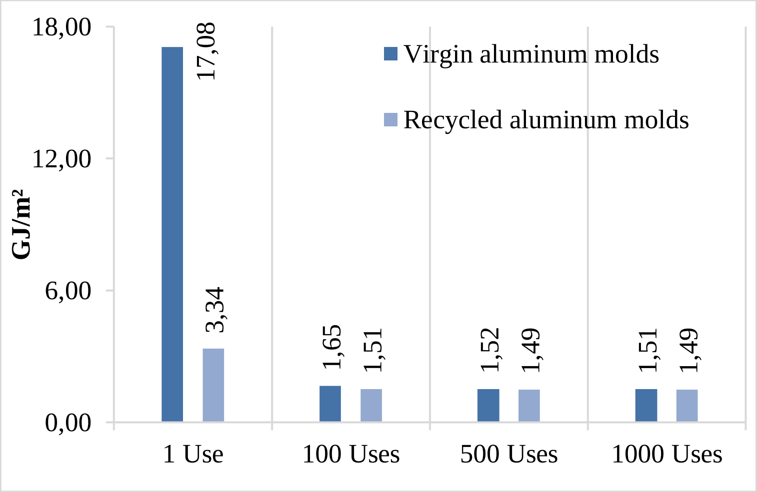


Figure 4 - **Pre-use energy of S4 using recycled aluminum molds and virgin aluminum molds for various uses**



There is also the possibility of using recycled aluminum for the manufacture of aluminum molds. In the first use there would be a great difference in the energy embedded in the scenario, however, with the increase of the uses this difference would be reduced as shown in Figure 4. Then, for the rest of this work, 100 reuses of virgin aluminum molds were considered.

In the use phase of the building, the energy that is used in the IEWS is the one of maintenance. In this case S1, S2 and S4 have similar performances, since they only require the painting service, however, S3 (steel frame) requires some material replacement, so this scenario required 1.48 GJ/m² as shown by Figure 5.

Figure 5 also shows the energy incorporated in the post-use phase, which involves demolition or deconstruction; the energy required by S3 is reduced in relation to the others, this is due to two factors: lower mass of this scenario and the deconstruction factor is smaller than that of demolition, as it does not require the use of large fossil-fueled engines.

Pedroso (2015) estimated the energy expenditure in demolition/deconstruction by means of prototype tests of 1.0 m². Using this methodology, the author obtained the value of 0.036 GJ/m² for conventional wall system (S1), 0.033 GJ/m² for load-bearing masonry (S2), 0.011 for steel framing (S3) and 0.030 GJ/m² for concrete wall (S4). These values do not consider human labor and the transportation of waste generated by deconstruction.

By analyzing the life cycle of the four scenarios, it is observed that S1 requires 3.19 GJ/m², S2 requires 2.89 GJ/m², S3 requires 3.47 GJ/m² and S4 demands 2.60 GJ/m². Therefore, considering the life cycle of the IEWS analyzed, S4 requires less amount of energy per square meter of construction and S3 has the highest demand.

By analyzing Figure 5 it can be seen that the phase of the life cycle that most influences the IEWS energy requirement is the pre-use phase, followed by the phase of use, whereas the post-use phase does not have great expressiveness. However, energy is only one of the environmental performance parameters of IEWS; the mass and volume of material to be discarded are some of the factors that must also be analyzed.

However, the energy spent with transport in S3 is significantly lower than in the other scenarios, as shown in Figure 6, which compares the energy spent on transport and the total gross energy of each scenario. This behavior can be explained by the specific mass of the steel frame system being smaller than the specific mass of the other wall systems.

Figure 5 - **Energy in the pre-use phase, use-phase and post-use phase of the live cycle of IEWS**

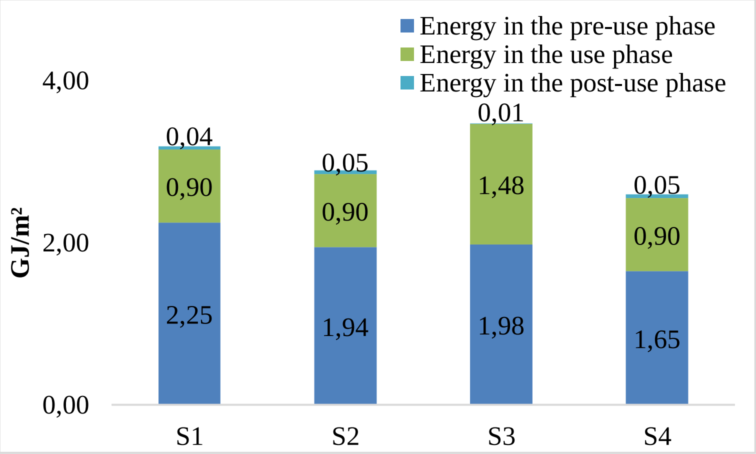


Figure 6 - **Comparison between the energy incorporated into the materials, energy spent on transport and the total gross energy of each scenario**

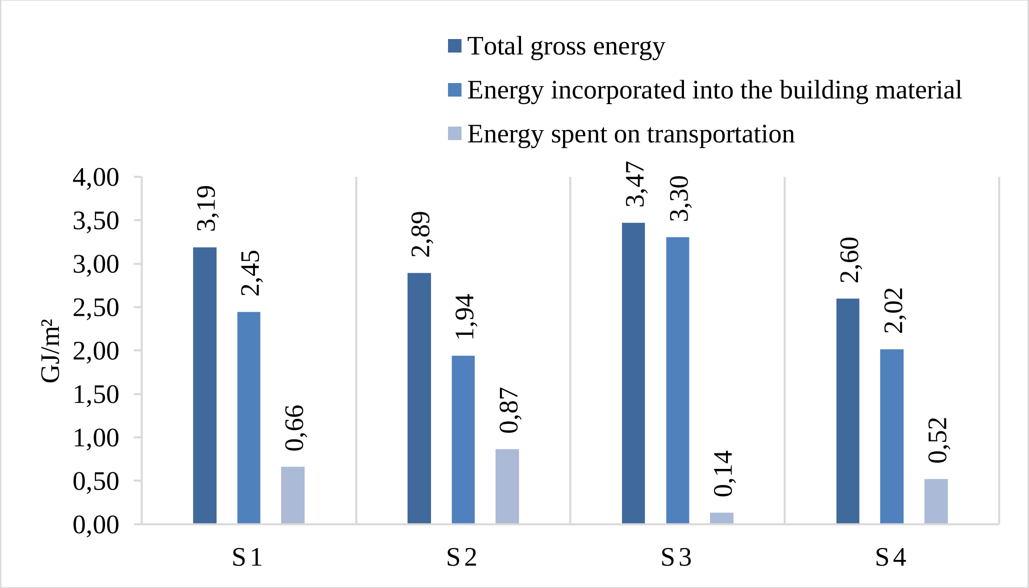


Figure 6 shows the comparison of the energy incorporated into the materials with the total gross energy of each scenario and also shows that a large part of the total gross energy of S3 is due to the incorporated energy of the building materials used in this system, which corresponds to 95.19% of the total gross energy. In the other scenarios this percentage is lower, in the conventional system the energy incorporated into the materials corresponds to 76.63% of the total gross energy, in the load-bearing masonry to 67.00% and in the wall of molded concrete on site this percentage is 77.64%.

Emissions from the life cycle of the IEWS

In a similar way to energy, CO_2 emissions are the majority in the pre-use phase, however, as it is possible to see in Figure 7, when the function of the LCA are the CO_2 emissions, S1 is the one with the highest values and S3 is the one which presents lower values in the pre-use phase.

As shown in Figure 7, in the use phase emissions are more significant in S3 due to the need to replace more materials than the other scenarios. In S1, S2 and S4 the values are the same, since the replacement of materials and the maintenance service are equivalent for all.

In turn, Figure 7 shows yet CO_2 emissions in the post-use phase. In this case, S3 is the one that has the lowest emission value; this is due to the method of disassembling the steel framing and its reduced mass.

Therefore, by analyzing CO_2 emissions throughout the life cycle of the IEWS, we can see that the scenario with the lowest value is S4. Adding the CO_2 emissions in the three phases S1 emits 87.22 kg. CO_2/m^2 of wall, S2 emits 82.04 kg. CO_2/ m^2 of wall, S3 emits 72.71 kg. CO_2/m^2 of wall and S4 emits 59. 67 kg. CO_2 $/m^2$ of wall.

Nabut Neto (2011) in a similar scenario to S1 computed 85 kg.CO_2/m^2 of wall. For a similar scenario to S4, Mequignon *et al.* (2013) obtained the value of 65.10 kg.CO_2/m^2.

S4 emits 5.81 kg. CO_2 per cubic meter of wall, however, in a study on emissions of concrete walls for soil containment Martí, Yepes and Molina-Moreno (2017) obtained 11.05 kg.CO_2/m^2, this occurs because retaining walls require a concrete with higher strength, which reflects in the higher consumption of steel and cement per cubic meter and, according to Zastrow *et al. (2017)*, cement and steel account for most of the energy embedded in retaining walls.

Islam *et al*. (2014) in a study of Australia's typical wall systems, ceramic brick, concrete block and wood closures, concluded that wood closures are responsible for a smaller amount of emissions than the others. Huang *et al*. (2018), in a study on energy incorporated in dormitories of Chinese universities also found that the structures of wood have lower emissions, thus, wood becomes another option for alternative wall systems in Brazil.

Figure 8 compares the emissions generated by transport with the total gross emissions of each scenario. S3 generates less emissions, this can be explained by the fact that this scenario requires less transport service for workers and materials.

Unlike emissions with transport, in the CO_2 emissions incorporated into the materials, that is, from the extraction, processing or manufacture of the materials, S3 is the one that generates more CO_2 emissions. Figure 8 shows that emissions from S1 and S3 generate near quantities.

Waste coming from the IEWS

With regard to the residues produced by each IEWS with wastes in the demolition or deconstruction, S1, S2 and S4 present close values, however, in S3 the mass of residues is considerably smaller (Figure 9).

Regarding Figure 9 and 6, we can see that the energy consumption is also not related to the mass of waste, since S3 is the one that has the highest energy consumption and is the lightest among the studied scenarios.

Comparing Figure 9 with Figure 8, we also can see that the mass of materials used in construction is not related to the mass of emissions, since S4, despite having the largest mass of waste, has the lowest CO_2 emissions.

General analysis of the life cycle of the IEWS

Figure 10 shows the CO_2 emissions and the energy incorporated into the life cycle of each scenario, from this it is possible to notice that S4 presents the lowest values for both functions; however, as shown in Figure 9, this same scenario generates the largest mass of waste.

Analyzing Figure 6 and Figure 8 we can note that transport and materials are responsible for great part of the energy consumed and CO_2 emissions. Bearing this in mind, Table 3 shows the percentages of energy and emissions from other sources and emphasizes that they are not values of great participation.

Figure 7 - **CO2 emissions in the pre-use phase, use-phase and post-use phase of the live cycle of IEWS**

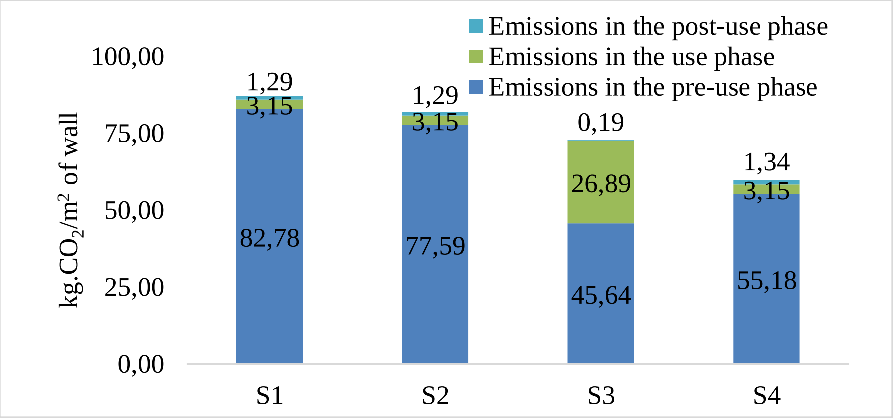


Figure 8 - **Comparison between emissions incorporated into the materials, emissions originating from transport and the total gross emissions of each scenario**

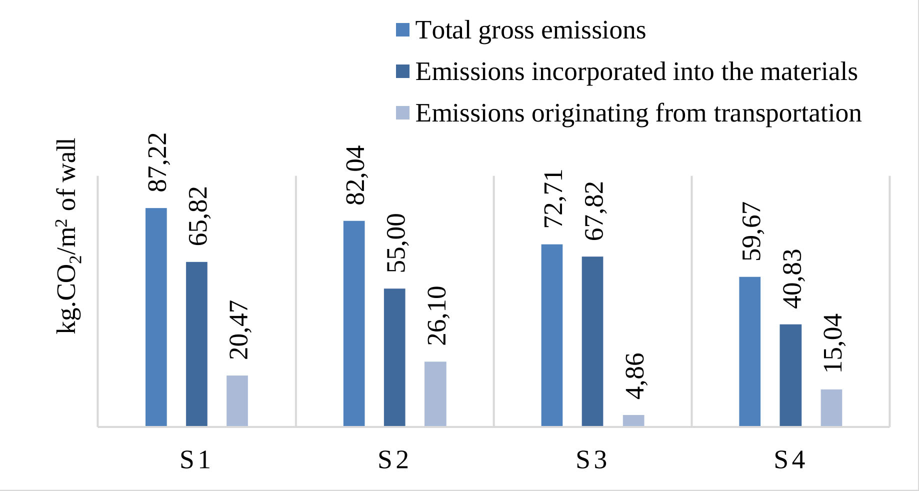


Figure 9 - **Mass of solid residue from wall systems including waste**

Figure 10 - **Comparison of the energy incorporated with the CO2 emissions in each scenario**

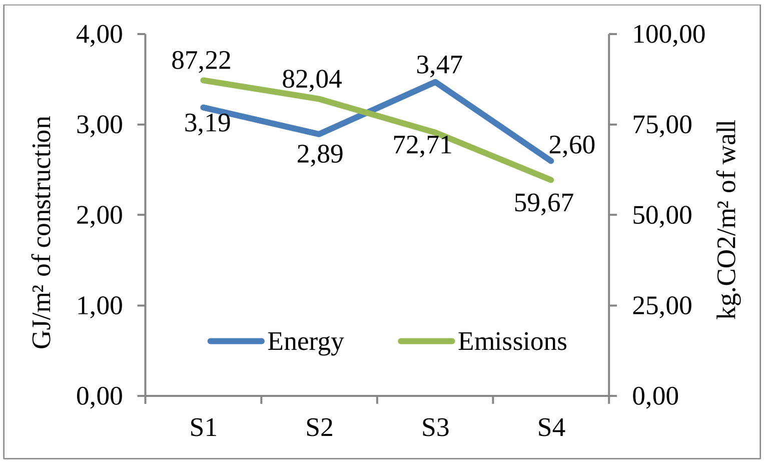


Table 3 - **Percentage of energy and emissions from labor and use of equipment**

Scenario	Percentage of energy spent on labor and equipment used in the building, maintenance and demolition (%)	Percentage of CO_2 emissions from the use of equipment (%)
S1	2.62	1.07
S2	3.02	1.15
S3	0.91	0.05
S4	2.21	3.87

Conclusions

Evaluating the energy life cycle and CO_2 emissions of wall systems for rural housing of social interest in Brazil, it is concluded that:

(a) S4 is the wall system with lower incorporated energy, considering that there are 100 different uses of the virgin aluminum molds. S4 is also the scenario that emits less amount of CO_2 during its life cycle, considering the same conditions of use of molds that had already been described;

(b) for the conditions of this study, the scenario that would consume more energy over the life cycle is S3;

(c) regarding CO_2 emissions, S1 scenario was less sustainable;

(d) we emphasize that this is a case study for the region of Cascavel, Paraná, and due to transport issues, the values of incorporated energy and CO_2 emissions can suffer significant variations for other regions; and

(e) one of the difficulties that ware found during the study was the lack of standardization of the measurement units.

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Revista da Associação Nacional de Tecnologia do Ambiente Construído
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