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## 1           **Impact of building material recycle or reuse on selected energy ratios**

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### 8           **Abstract**

9           While the energy evaluation method has been used successfully in recycling processes,  
10           this area of application still requires further development. One of such is developing  
11           energy ratios or indices that reflect changes depending on the number of times a material  
12           is recycled. Some of these materials may either have been recycled or reused  
13           continuously as inputs to a [building, for example](#), and thus could have various impacts on  
14           the energy evaluation of the building. The paper focuses on reuse building materials [in](#)  
15           [the context](#) of environmental protection and sustainable development. It presents the  
16           results of an energy evaluation of a low-energy building (LEB) in which a percentage of  
17           input materials are from recycled sources. The corresponding impacts on the energy yield  
18           ratio (EYR<sub>B</sub>) and the [environmental](#) loading ratio (ELR<sub>B</sub>) are studied. [The EYR which is the](#)  
19           [total energy used up per unit of energy invested, is a measure of how much an](#)  
20           [investment enables a process to exploit local resources in order to further contribute to](#)  
21           [the economy. The ELR however, is the total nonrenewable and imported energy used up](#)  
22           [per unit of local renewable resource and indicates the stress a process exhibits on the](#)  
23           [environment.](#) The evaluation provides values for the selected ratios based on different  
24           recycle times. Results [show](#) that values of the energy indices vary, even more, when  
25           greater amounts of material is recycled with higher amount of additional energy required  
26           for recycling. This provides relevant information prioritizing the selection of materials for  
27           recycling or reuse in a building, and the optimum number [of reuse or recycle times of a](#)  
28           [specific material.](#)

29           Keywords: Energy, Recycle, Low-energy building

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## 1    **1.    Introduction**

2        Almost 40% of the world's consumption of materials converts to the built environment,  
3        and about 30% of energy use is due to housing (Pulselli et al., 2007). The building sector  
4        is the biggest consumption sector, before transports sector. As a result, there are ongoing  
5        research works [to investigate how to significantly](#) reduce the consumption of energy and  
6        material flows in the building industry. In effect, terms such as low-energy and passive  
7        house are used more frequently all over Europe.

8        Reuse and recycling of building material is a growing area of interest and concern in  
9        many parts of the world. Current practices and trends in the building material waste  
10       [management are](#) examined from a building life cycle standpoint or cradle to grave  
11       concept. To evaluate buildings and their environmental impacts more effectively, several  
12       tools and methods are adopted. These methods provide a list of indicators, based on  
13       objective values that compare buildings' performances and impacts to their environmental  
14       constraints. Some examples of these are the life cycle analysis (Guinée et al., 2001), [the](#)  
15       energy analysis (Odum, 1996), the ecological footprint (Rees & Wackernagel, 2004), and  
16       the exergy analysis (Szargut et al., 1988). All of these assessments are needed to develop  
17       a comprehensive waste management plan for specific projects.

18       The use of construction waste management techniques which rely on recycle and reuse  
19       of materials have proven to have economic benefits for the construction industry (Kralj,  
20       2007). Reuse is a means to prevent solid waste from entering the [landfill, and](#) increase the  
21       material, educational and occupational wellbeing of citizens by taking useful products  
22       discarded by those who no longer want them and providing them as inputs to [the](#)  
23       construction of buildings. In many cases, reuse reduces raw material inputs to a very large  
24       extent. This is important since a significant percentage of the total natural resources that  
25       are used in industrialized countries are exploited by the building industry (Peuportier et  
26       al., 1996). High quantities of raw material inputs for building construction results in high  
27       energy required for the extraction and processing of these materials.

28

1       Emergy evaluation has been widely applied in the evaluation of ecological systems,  
2 energy systems, and environmental impacts of processes, generating a large number of  
3 studies. Yet, despite such a wide debate, only a few studies have been produced  
4 concerning applications of emergy evaluation to building construction and to building  
5 materials. In most of these studies, emergy evaluation is employed as an environmental  
6 indicator for construction activities, building materials production and recycling  
7 (Buranakarn, 1998; Odum, 2002; Brown & Buranakarn, 2003; Huang & Hsu, 2003;  
8 Meillaud et al., 2005; Pulselli et al., 2007). Odum (2002) presents a broad approach to the  
9 relationships of building construction with materials circulation and energy hierarchy.

10       In the emergy approach, buildings are a storage of materials that is the sum of the  
11 inputs during the construction process. This storage loses emergy as building materials  
12 depreciate along time and become dispersed in the environment. New inputs by means of  
13 maintenance and repair actions keep the emergy flow into the building system.

14       Buranakarn (1998) and Brown & Burnakarn (2003) proposed a set of emergy indices  
15 to evaluate recycling patterns and recyclability of building materials. These emergy indices  
16 are suggested to measure the environmental benefits of three recycling trajectories:  
17 material recycle, by-product use, and adaptive reuse, i.e. recycling the material for a  
18 different purpose. The reuse option in the sense of reusing a product elsewhere was not  
19 considered in these studies. Emergy per mass is also pointed as a good indicator for  
20 recyclability. Buranakarn (1998) and Brown & Burnakarn (2003) also recognize that  
21 materials with higher emergy per mass are more suitable for being recycled by human  
22 systems due to their 'quality', and have more environmental impacts when released to the  
23 environment. In the context of an environmental approach, Huang & Hsu (2003) proposed  
24 a set of indicators based on emergy to measure the effects of construction in Taipei's  
25 sustainability: (a) intensity of resource consumption; (b) inflow/outflow ratio; (c) urban  
26 livability; (d) efficiency of urban metabolism; and (e) emergy evaluation of urban  
27 metabolism. The relevance of emergy analysis for that study was in the fact that it  
28 enabled the consideration of biophysical value of resources to the economic system.  
29 Evaluation of main emergy flows of materials used due to urban construction provided

1 both an understanding of their relative value and contribution to the [ecological-economic](#)  
2 system (urban construction is equivalent to 44% of the Energy used in Taipei), and a  
3 measure of the ecological interface of rapid urban development (environmental load of  
4 construction waste generation and recycling opportunities).

5 Meillaud et al. (2005) applied emergy analysis to evaluate an experimental building of  
6 three stories containing faculty and students' offices and a workshop, built in 1981, by  
7 including environmental, economical, and information flows. By including information flows  
8 generated by building occupants to the analysis of the whole building system, it was  
9 possible to calculate the outputs generated by the building usage: emergy per educated  
10 [student, emergy per publication, emergy per course and emergy per 'service'](#). The  
11 significance of emergy per unit was highlighted by Meillaud et al. (2005), [since](#) there were  
12 few available emergy per unit references for most commodities [as inputs to a building](#).

13 Another application of emergy to building construction was published by Pulselli et al.  
14 (2007). The authors proposed a set of environmental indices to provide a basic approach  
15 to environmental impacts of buildings by accounting for the main energy and materials  
16 inflows within the building construction process, maintenance, and use:

- 17 (i) Building emergy per volume ( $E_m$ -building volume): this represents the  
18 'environmental cost' of the building;
- 19 (ii) Building emergy to money ratio ( $E_m$ -building/money ratio): this represents the  
20 ratio of total Energy used to money (seJ/€);
- 21 (iii) Building emergy per person ( $E_m$ -buildings per person): this represents the rate of  
22 Emergy use of human systems with relation to buildings.

23 The proposed indices based on emergy accounting provide a framework for evaluating  
24 and comparing different building typologies, technologies and materials, regarding  
25 different manufacturing processes, maintenance, use, thermal efficiency and energy  
26 consumption. Pulselli et al. (2007) argue that buildings are like full emergy reservoirs  
27 (storage) that persists in time, and that emergy evaluation of a building highlights the  
28 durability of materials as a factor for sustainability. With reference to building materials,

1 the most extensive Energy study was developed by Buranakarn (1998) in order to identify  
2 recycling patterns. The author analyses several common materials.

3  
4 The main aim of this paper is to extend the energy based methodology to continuous  
5 matter reuse as devised by Amponsah et al. (2011) to a process. In fact, authors consider  
6 that the additional energy (coming from each recycle matter) can be aggregated to the  
7 "classical" energy evaluation which does not include any recycling. The different impacts  
8 this continuous reuse might have on the energy yield ratio (EYR) and the environmental  
9 loading ratio (ELR) on the whole process require new definitions.

10 The rest of this paper is organized as follows: in section 2, relevant literature on  
11 energy evaluation and its application in buildings are reviewed. The methodology  
12 developed by Amponsah et al. (2011) is outlined and defined in its specific context. In  
13 Section 3, a case study is presented on a low energy building that corresponds to the  
14 present construction standards in France. Section 4 presents a discussion and finally,  
15 section 5 concludes the paper.

## 16 17 **2. Materials and methods**

18 With reference to the work and formulae developed by Buranakarn (1998) and  
19 Amponsah et al. (2011) respectively, the output energy of a system involving recycle  
20 inputs differs marginally from a similar system with 100% raw material inputs. Amponsah  
21 et al. (2011) further explained that the continuous recycling of a specific material due to  
22 the additional energy required at each stage of recycle, impacts on the final output  
23 energy of the system usually increasing the output energy after each additional recycle.

24 As such, authors of the said paper pointed out that the specific energy of any  
25 material  $e_m$ , containing a recycled part (or reused part)  $q_m$ , has a dynamic equation at  
26 discrete time, see equation (1), according to the specific total energy inputs  $e_{mi}$  (energy  
27 of raw material, fuel, goods and services etc.) without recycle, and the specific additional  
28 energy needed for recycling (for reusing)  $e_{mc}$ . The sampling time for recycling is noted  $T_e$

1 and the recycling number is noted  $n_m$ . As such the discrete time  $t$  is just equal to the  
 2 product  $Te$  by  $n_m$ . For unitary amount of matter, one gets:

$$3 \quad e_m(t) = e_{mi}(t)(1 - q_m(t)) + e_{mc}(t) + q_m(t) e_m(t-1) \quad (1)$$

4 The specific energy of any matter at the  $n^{\text{th}}$  recycling is the sum of three terms: the  
 5 specific energy of raw material adjusted to its raw mass, the specific additional energy  
 6 adjusted to its recycled part and the part coming from the past within the matter itself  
 7 adjusted to its recycled part. Amponsah et al. (2011) detailed that there is no double-  
 8 counting in this decomposition and the pathway of the recycled matter is followed.

9 Equation (1) is in a general form. Assuming that the specific energy inputs  $e_{mi}$  and  
 10 the specific additional energy needed for recycling  $e_{mc}$  and the recycled part  $q_m$  are  
 11 independent of the discrete time, the specific energy of matter containing a recycled part  
 12 can be easily calculated by underlying the sum of a geometric series, noted  $\psi$  :

$$13 \quad e_m(1) = e_{mi} + e_{mc} q_m \text{ for the 1}^{\text{st}} \text{ Recycle, where the factor } \psi = q_m \quad (2)$$

$$14 \quad e_m(2) = e_{mi} + e_{mc}(q_m + q_m^2) \text{ for the 2}^{\text{nd}} \text{ Recycle, where } \psi = q_m + q_m^2 \quad (3)$$

$$15 \quad e_m(3) = e_{mi} + e_{mc}(q_m + q_m^2 + q_m^3) \text{ for the 3}^{\text{rd}} \text{ Recycle, } \psi = q_m + q_m^2 + q_m^3 \quad (4)$$

$$16 \quad e_m(4) = e_{mi} + e_{mc}(q_m + q_m^2 + q_m^3 + q_m^4) \text{ for the 4}^{\text{th}}, \psi = q_m + q_m^2 + q_m^3 + q_m^4 \text{ and so on.} \quad (5)$$

17  
 18 Energy evaluation classifies inputs into three categories: purchased, renewable, and  
 19 non renewable. On the basis of these classes, some indicators can be computed in order to  
 20 assess the sustainability of the use of resources (Lagerberg;1999):

- 21     ▪ the energy yield ratio (EYR) is the energy of an output divided by the energy  
 22       of those inputs to the process that are purchased from the economy;
- 23     ▪ the energy investment ratio (EIR) is the purchased energy from the economy  
 24       (services and other resources) divided by the free energy inflow from the  
 25       environment.
- 26     ▪ the environmental loading ratio (ELR) is the ratio of purchased and non-  
 27       renewable indigenous energy to free environmental energy.

On this basis, Amponsah et al. (2011) extended these ratios to some dimensionless energy indices for a single recycled material. Assuming that the energy inputs  $e_{mi}$  and  $e_{mc}$  and the recycled part  $q_m$  are constant, these ratios are in connection with the pathway of the recycled material by the number of recycle times. Thus, by means of the geometric series:

$$EYR_m(q_m, n_m) = \frac{(e_{mi} + \psi e_{mc})}{(e_{miF} + \psi e_{mcF})} \quad (6)$$

$$EIR_m(q_m, n_m) = \frac{(e_{miF} + \psi e_{mcF})}{(e_{miN} + \psi e_{mcN}) + (e_{miR} + \psi e_{mcR})} \quad (7)$$

$$ELR_m(q_m, n_m) = \frac{(e_{miF} + \psi e_{mcF}) + (e_{miN} + \psi e_{mcN})}{(e_{miR} + \psi e_{mcR})} \quad (8)$$

Where  $e_{mi}$  is the specific energy of raw material use without recycle, and  $e_{mc}$  is the additional energy needed for recycling. Their renewable part is indexed by  $R$ , the non renewable part by  $N$  and the purchased part by  $F$ , so  $e_{mi} = e_{miF} + e_{miR} + e_{miN}$ , see figure 1.

Figure 1: Energy flows with additional energy for recycling

Energy source is noted SE.

If only one single matter with its associated pathway is considered, the total energy for processing is increased by its additional energy  $\Delta E_{mc}(q_m, n_m)$ :

$$\Delta E_{mc}(q_m, n_m) = m_m e_{mc} q_m \left( \frac{q_m^{n_m} - 1}{q_m - 1} \right) \quad (9)$$

where  $m_m$  is the mass of the considered material,  $q_m$  is its mass fraction of recycle,  $n_m$  is its number of recycle,  $e_{mc}$  is the specific energy required for 100% recycle.

For  $M$  recycled materials in a process indexed by  $P$ , such as building manufacturing, dimensionless ratios for the entire process can be defined as:



$$EYR_p = \frac{E_p^0 + \sum_{j=1}^M \Delta E_{jc}(q_j, n_j)}{E_{PF}^0 + \sum_{j=1}^M \Delta E_{jCF}(q_j, n_j)} \quad (10)$$

$$EIR_p = \frac{E_{PF}^0 + \sum_{j=1}^M \Delta E_{jCF}(q_j, n_j)}{E_{PN}^0 + E_{PR}^0 + \sum_{j=1}^M (\Delta E_{jCN}(q_j, n_j) + \Delta E_{jCR}(q_j, n_j))} \quad (11)$$

$$ELR_p = \frac{E_{PF}^0 + E_{PN}^0 + \sum_{j=1}^M (\Delta E_{jCF}(q_j, n_j) + \Delta E_{jCN}(q_j, n_j))}{E_{PR}^0 + \sum_{j=1}^M \Delta E_{jCR}(q_j, n_j)} \quad (12)$$

Where  $E_p^0$  is the total energy of the process without any recycle matter.  $E_{PF}^0$ ,  $E_{PR}^0$  and  $E_{PN}^0$  are respectively its purchased, renewable and non renewable part. The additional energy of the  $j^{\text{th}}$  matter  $\Delta E_{jc}$  is also decomposed into its three parts (purchased, renewable, and non renewable).

Buranakarn (1998) obtained the value for the main materials likely to be recycled in building construction:

- bricks:  $e_{bi}(100\%) = 3.68E+09$  seJ/g, when reused  $e_{bc}(100\%) = 2.6E+05$  seJ/g and when recycled  $e_{bc}(100\%) = 4.8E+05$  seJ/g, see Amponsah (2011, p158-160)
- steel via the electric arc furnace process:  $e_{si}(100\%) = 4.15E+09$  seJ/g,  $e_{sc}(100\%) = 9.0E+07$  seJ/g, see Buranakarn (1998, p52)
- aluminium:  $e_{ai}(100\%) = 1.27E+10$  seJ/g,  $e_{ac}(100\%) = 6.4E+08$  seJ/g, see Buranakarn (1998, p60)
- plastic lumber:  $e_{pi}(100\%) = 5.75E+09$  seJ/g,  $e_{pc}(100\%) = 5.8E+08$  seJ/g, see Buranakarn (1998, p76)

### 3. Case Study

Low energy buildings involve the reduction of fossil fuel use such as oil, gas and coal, which enhances sustainable building and development. There are many ways to make a building energy-efficient: by high insulation, using building components resulting in less thermal bridges, buildings with good air tightness or by technical installations such as mechanical heat recovery ventilation, which also benefits the indoor climate (Andersson et al, 2006; Wargocki and Wyon, 2007).

1 The building studied is located in Theys (Isère) which is a small town 30 km far from  
2 Grenoble. It is defined by a net area of 155 m<sup>2</sup> calculated as the sum of the living area  
3 plus the garage area. It is intended for residential use. It comprises a basement, a ground  
4 floor and one other floor. The structure consists of a reinforced concrete frame with pillars  
5 and beams. The walls are made of concrete blocks with an internal insulation layer and  
6 gypsum plastering. The external wrapping is formed by two side walls (adjoining blocks),  
7 two facades (brickwork with cavities), an insulated basement. The upper ceiling is covered  
8 with mineral wool, under clay tiles roof. The house is heated by a natural gas boiler. The  
9 aluminum glass windows are double glazed with an overall heat transfer coefficient of  
10 1.1 W/m<sup>2</sup> K. The annual heating consumption is of 50 kWh/m<sup>2</sup>, corresponding to the  
11 upper limit for the French label low-energy building.

12  
13 An inventory of inputs to the construction process with relative raw data has been  
14 drawn and the quantity of materials and their compositions are reported in a succession of  
15 steps that cover from the first to the last brick settled. Raw data (mass quantities) in the  
16 building metric computation has been reported in Table 1, and has been processed  
17 through the relative transformities and expressed in terms of solar energy joules.  
18 References for transformities used in the table are from: Odum et al. (2000); Brown and  
19 Buranakarn (2003); Meillaud et al. (2005); Odum (1996).

20  
21 Table 1. Emergy evaluation Table

22 Emergy flows have been reported relative to the materials used to build each component  
23 and structural part. In this case, human labor is not considered. The composition and the  
24 percentage of the main building materials used, assists in knowing the main material  
25 inputs for the construction of the building. The subsequent emergy results enable us to  
26 make a list of building materials based on their 'environmental cost' (in terms of seJ) that  
27 depends on both their quantity and their transformity (quality).

28  
29 Major comments on table 1 are the following:

- 1       ▪ Line 1, the sun primarily serves as a source of light for site workers during the daytime
- 2       of work. The sun also helps in drying material used in construction (such as, concrete,
- 3       mortar, paints, etc...), see Pulselli et al. (2007) and Meillaud et al. (2005).
- 4       ▪ The electricity breakdown used, come from the energy mix in France, see website
- 5       U.E. 2007. Since electric energy is purchased to national grid, authors chose to
- 6       make no distinction from the source.
- 7       ▪ The renewable energy part of whole building construction is considered as the sum
- 8       of sun and water energy. Its purchased energy part is considered as the sum of
- 9       fuel and electricity energy.
- 10      ▪ In Table 1, the value of transformities corresponds to a process with no recycling.
- 11      Without any recycled material, the total energy for building manufacturing, noted
- 12       $E_B^0$ , is 7.11E+16 seJ, sharing in its renewable inputs (line1&2)  $E_{BR}^0$ , in its non
- 13      renewable inputs (line 3-65)  $E_{BN}^0$  and in its purchased inputs (line 66-70)  $E_{BF}^0$ . The
- 14      index B refers to building construction, the process studied in the case study, and
- 15      the exponent 0 refers to any recycled material.
- 16      ▪ It is observed that concrete takes about 74% in mass of the entire material inputs
- 17      of the building followed by bricks.

18

19       Energy values of the main individual materials are also presented in Fig. 2. It can

20       again be observed that concrete still remains a significant material not only in quantity use

21       but also in terms of its energy **input to the building**. This is because although concrete

22       does not have a too high transformity value, it is used in a very large proportion in **the**

23       **construction and** thus it becomes responsible for a large share of the total energy (65%)

24       of the total **material input**.

25  
26  
27  
28

Figure 2. Energy inputs of main raw materials in constructing the building

1 Fig. 2 shows, however, that limestone (which has the third largest input  
 2 quantitatively) falls out when emergies are considered. This is explained by the low  
 3 transformity value (1.68E+09 seJ/kg) of limestone. Inversely, PVC, though slightly low in  
 4 consumption, have a high value of transformity (9.86E+12 seJ/kg). This makes PVC a  
 5 good choice for recycling or reuse, since it has a high embodied energy per unit mass.  
 6 Nevertheless, PVC cannot have a significant effect on the emergy of the building  
 7 construction.

#### 8 4. Discussion

9 First, authors consider only one matter, the bricks, since they were found to be the  
 10 second most used material in the construction of the building (after concrete), accounting  
 11 for about 19% of the total material input. Though it might not be the best example of a  
 12 reusable or recyclable material in building, compared to PVC, steel etc, the idea is to  
 13 illustrate the developed procedure of emergy evaluation. The emergy of the building is  
 14 thus re-evaluated, taking into account different scenarios. As such, emergy for sorting,  
 15 collection and transportation to the recycling plant is considered, in addition to the emergy  
 16 for the plant process. This emergy adds up to give the additional emergy of bricks  
 17 recycling ( $\Delta E_{bc}$ ). For this building, the specific emergy of bricks (with a total mass of 3767  
 18 kg) is  $e_{bc} = 2.6E+05$  seJ/g if 100% reused and  $e_{bc} = 4.8E+05$  seJ/g if 100% recycled.  
 19 Numerical application gives an emergy of 9.9E+11 seJ when reused and 1.81E+12 seJ  
 20 when recycled. This is then multiplied by the quantity ( $q_b = 30\%$  in this case) of recycled  
 21 (or reused) bricks. Authors assume that this additional emergy  $\Delta E_{bc}(q_m, n_m)$ , corresponds  
 22 mainly to collection and separation, and is incorporated only in purchased inputs  
 23  $\Delta E_{bcF}(q_m, n_m)$ . Equation (10) begins:

$$24 \quad EYR_B = \frac{E_B^0 + \Delta E_{bcF}(q_b, n_b)}{E_{BF}^0 + \Delta E_{bcF}(q_b, n_b)} \quad (13)$$

- 25 ■ The result for the first reuse ( $q_b$   $e_{bc}$ ) is added up to the initial emergy of the  
 26 building (ref. Table 1) 7.1E+16 seJ giving an emergy difference of 5.4E+11 seJ.  
 27 Results for recycled bricks are proposed in Table 2, in the case of 30% recycle rate  
 28 of bricks ( $q_b$ ) and for different number of times of recycling.

- 1       ▪ For the first reused bricks, the numerical application gives the energy difference of  
2       2.99 E+11 seJ. Results for reused bricks are proposed in Table 3 always in the case  
3       of 30% reuse part and for different number of times of reuse.

4  
5       This is continued for different number of times of recycle and for different quantities to  
6       assess the various impacts on the energy analysis of the building (refer to equations 2 to  
7       5).

8  
9       Table 2. Energy results for bricks recycling for different recycling times.  
10

11  
12  
13       Table 3. Difference in energy involving a part of material recycle and initial energy of building for  
14       reuse of bricks (e.g. in concrete mix)  
15  
16

17       The same scenario is used to analyze the various effects on the energy yield ratio. It  
18       is seen from the results presented that the EYR decreases with respectively an increase of  
19       recycling time in Fig. 3a and reusing time in Fig 3b. This is explained by the increase of  
20       additional goods and services purchased to aid in the recycling process. Figs. 4a and 4b  
21       show respectively the potential impact of recycled bricks (Figure 4a) and reused bricks  
22       (Figure 4b) on the energy yield ratio ( $EYR_B$ ) of the building. Without any recycling  $EYR_B$  is  
23       the ratio of the total energy for building construction (7.11 E+16 seJ) to the energy part  
24       purchased from economy (1.98 E+13 seJ). Numerical application gives 3.59E+3. This  
25       value means that the purchased energy part is low. As presented in table (2) for recycling  
26       or table (3) for reusing, the additional energy  $\Delta E_{bc}(q_m, n_m)$  is about 1% of  $E_{BF}^0$  so the  
27       bricks recycling, or the bricks reusing, has a low impact on the ratio  $EYR_B$  for the building  
28       construction, see Figs 3a and 3b. Since bricks reusing energy is approximately half the  
29       one for recycling, the impact of reusing on  $EYR_B$  is lower than the one for recycling. The  
30       greater the number of recycling (or reusing) is, the lower the  $EYR_B$  is and consequently  
31       the proportional part of purchased economy increases, see Figs 4a and 4b.

1 Common sense has it that both recycling and reusing tend toward sustainability.  
2 Hence, Ulgiati et al. (2004) proposed a path of energy allocation in which the energy  
3 rules not violated. In this, the energy invested in the treatment and recycling process  
4 should be assigned to the recycled resource. As such, the proposal suggests that wastes  
5 only bear the additional energy inputs needed for their further processing. Ulgiati et al.  
6 (2004) then amounted to 'resetting' the energy content in recycling processes to eliminate  
7 the problem of cumulative energy.

8  
9

10 Figure 3. Impact of 30% (constant rate) continuous bricks recycle (a) and reuse (b) on  
11  $EYR_B$  of the building

12  
13 Figure 4. Impact of different recycling rates for continuous bricks recycle (a) and reuse (b)  
14 on  $EYR_B$  of the building

15  
16

17 Authors consider one additional material, the plastic, its mass is 171 kg and its  
18 specific recycle energy is  $5.8 \text{ E}+08 \text{ seJ/g}$ . For 30% of recycled part, the value of the first  
19 recycling ( $2.98 \text{ E}+13 \text{ seJ}$  corresponding to the product of specific transformity  
20  $5.8\text{E}+13 \text{ seJ/kg}$  by its mass 171 kg and by its recycle part 30%) is greater than the  
21 purchased energy for the building construction ( $1.98 \text{ E}+13 \text{ seJ}$ ). So the impact of plastic  
22 recycling is very significant on  $EYR_B$ , see Fig. 5. Fig.6 shows the impact of recycled plastic  
23 on the energy yield ratio ( $EYR_B$ ) of the building.

24  
25  
26

Figure 5. Impact of 30% (constant rate) continuous plastic recycle on  $EYR_B$  of the building

27 Figure 6. Impact of different recycling rates for continuous plastic recycle on  $EYR_B$  of the  
28 building

29  
30

31 As can be seen in the results of the  $EYR_B$ , ignoring the impact of material reuse or  
32 recycling leads to the loss of significant information. Extending the traditional  $EYR_B$  to  
33 include the recyclable values from the additional energy needed for recycling, increases  
34 the value associated to the purchased goods and services and thus reduces the  $EYR_B$ . It is

1 observed that  $EYR_B$ s are lower in higher recycling times. For instance, the difference  
2 between  $EYR_B$  for a 1<sup>st</sup> recycle and a 5<sup>th</sup> recycle is quite significant (3.92E+01). This is due  
3 to the significant changes in the additional energy amounts needed for the cycle of  
4 material recycling or reuse.

5  
6 In the case only one material is recycled (or reused), bricks for example, the energy  
7 loading ratio for building construction  $ELR_B$  is defined as:

$$8 \quad ELR_B = \frac{E_{BF}^0 + E_{BN}^0 + \Delta E_{bcF}(q_b, n_b)}{E_{BR}^0} \quad (14)$$

9  $ELR_B$  is increasing with both the recycle part (or reuse part), and the number of  
10 cycles. A higher  $ELR_B$  suggests that investing in waste management causes more  
11 environmental stress. This is due to the fact that the purchased inputs from the economy  
12 needed for recycling, or reusing, increase.

13  
14 Figure 7. Impact of different recycle rates (a) and reuse rates (b) for continuous bricks  
15 recycle on  $ELR_B$  of the building  
16

17 Fig.7a and 7b show that the developed methods if utilized would serve as an  
18 extension to quantify and interpret the attributes of systems with percentages of  
19 respectively recycled inputs and reused inputs, with important implications in comparative  
20 decision making.

21  
22 Before conclusion, authors would like to emphasize on two major points

- 23 ▪ Equations (10-12) have been introduced to study the impact of several recycled  
24 materials (or reused) with different parts and at different numbers of recycling (or  
25 reusing) on energy assessment of a process. In this paper, it does not worth it to  
26 multiply numerical applications. It is possible to mix the assessment of bricks and  
27 plastic recycling, and so on.... This paper provides the method.
- 28 ▪ It is very important to know the industrial process for recycling (or reusing), in  
29 other words the pathway of the recycled (or reused) material. In this paper,  
30 authors have considered that this industrial process is based on collection and

1 separation, and have allocated this additional energy as a purchased energy. If  
2 one wants to allocate it to the product itself, by increasing its transformity in  
3 energy table (as Table 1), then the additional energy is considered in the non  
4 renewable part in the energy assessment of a process. In this case of building  
5 construction, recycling and reusing would not have any impact on the ratios  $EYR_B$   
6 and  $ELR_B$  because the value  $E_B^0$  is so significant that the additional energy is  
7 negligible.

## 9 **5 Conclusion**

10 Energy can be used successfully to evaluate systems with a fraction of its input  
11 materials derived from recycle sources, by effectively following the pathway of the  
12 material during the entire process (avoiding double counting). In this paper the  
13 methodology proposed by Amponsah et al. (2011) is applied and exemplified in the  
14 energy evaluation of a low energy building in France. The evaluation results reveal  
15 significant impacts on the energy yield ratio ( $EYR_B$ ) and the energy loading ratio ( $ELR_B$ ) of  
16 the building having a fraction of its input materials from recycled sources. The proposed  
17 methodology is important to provide the link between the energy evaluation method and  
18 the hidden information in recycling materials severally. This is very useful for evaluating  
19 and improving systems which often have recycled inputs, to compare the usefulness of  
20 using raw material inputs or recycled inputs. Moreover, it enables an investigator to select  
21 optimum levels of recycling (amount to recycle and number of times of recycle) to achieve  
22 greater results towards sustainability. From the case study, every process in which a  
23 fraction of inputs can be traced to recycle sources, can be evaluated simply by applying  
24 the factor  $\psi$ . In this way the difficulty of recalculations is somehow reduced, since the  
25 factor could easily be selected depending on the time of recycling (1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> etc  
26 recycling). The results of  $EYR_B$  and  $ELR_B$  substantiate the need for the continuous  
27 development of energy as a useful analytical tool, due to its ability to account for the  
28 contribution of ecosystems to economic activity. Furthermore, energy provides useful



1 indicators for evaluating the ecological feasibility as well as sustainability of [construction](#)  
2 [processes and buildings](#). The improved indicators proposed in this work provide a  
3 conceptually sound basis to quantify the impacts of recycling or reuse of materials in a  
4 typical low energy building. The calculated indicators were shown to be consistent with the  
5 notion that investing in waste management must be expected to lead to less  
6 environmental stress largely dependent on the input materials either from renewable, non  
7 renewable or purchased sources. A good balance of these would enhance sustainability.

8  
9 In future works, it could be interesting to consider the emergy assessment for automotive  
10 since the part of recycling is rather important in this sector (up to 90%). The consumer goods  
11 sector should also be studied through the emergy assessment as it is a non-negligible natural-  
12 resources consumption (e.g. packaging: metal cans, glass cans, paper, cardboard...).

13

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19 [for their helpful comments.](#)

20

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25

Figure 1

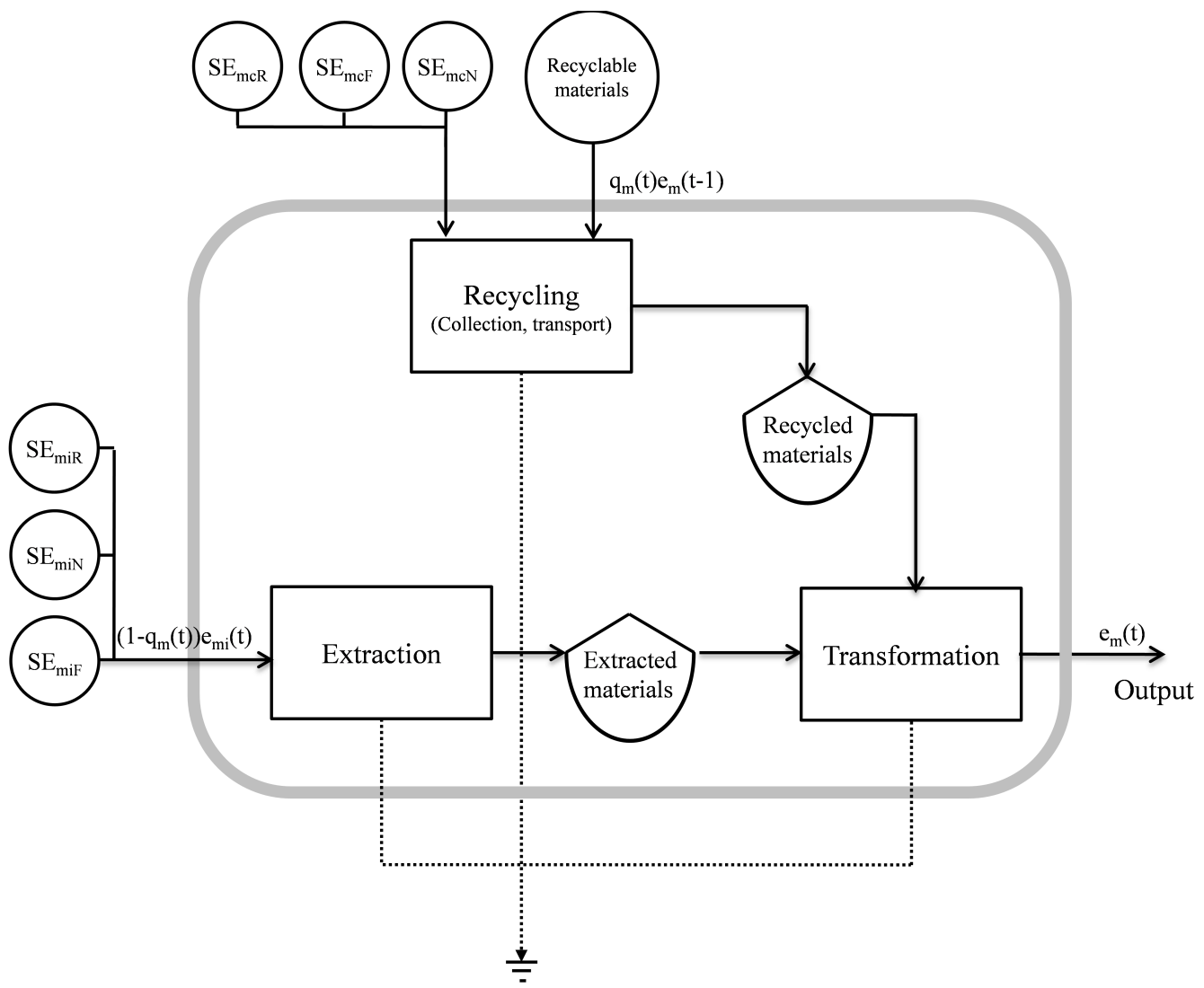


Figure 2

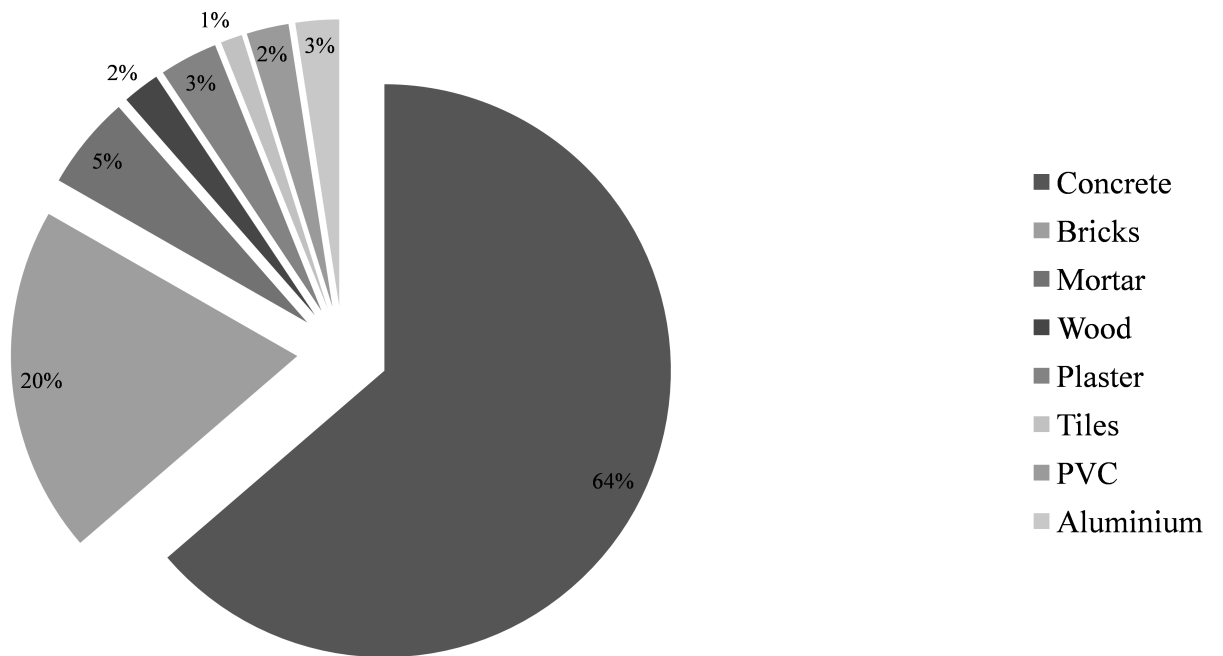


Figure 3a

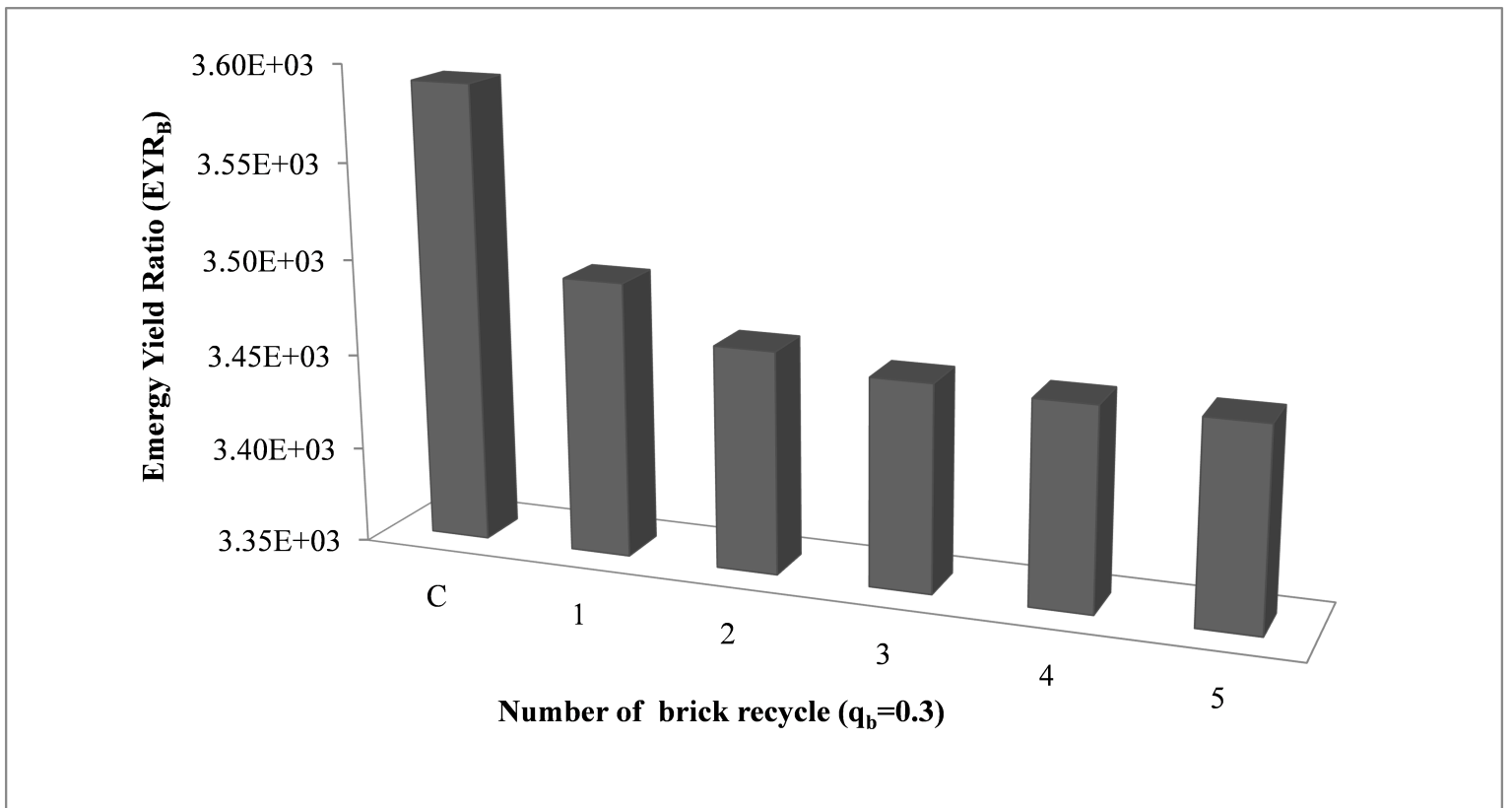


Figure 3b

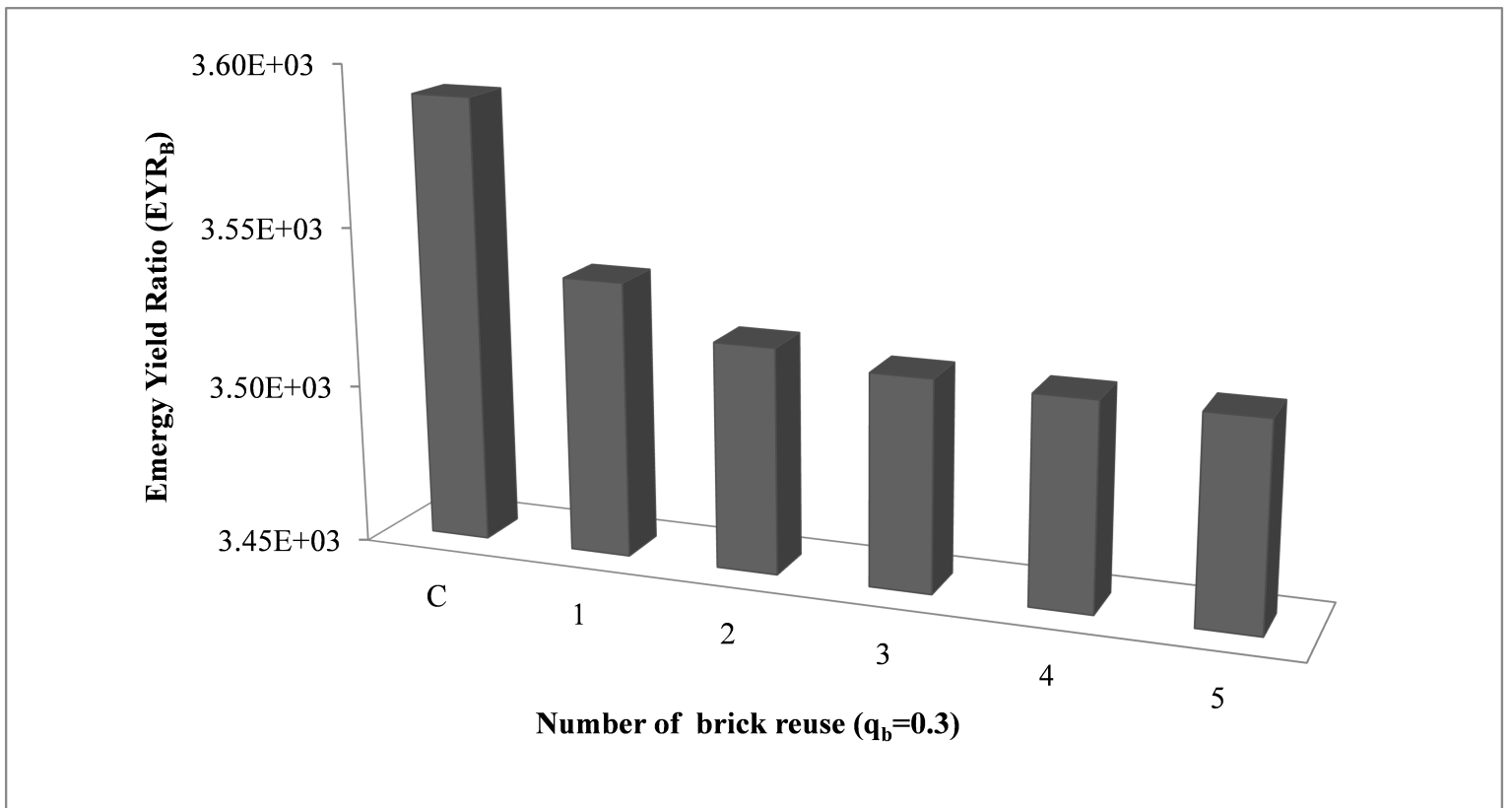




Figure 4a

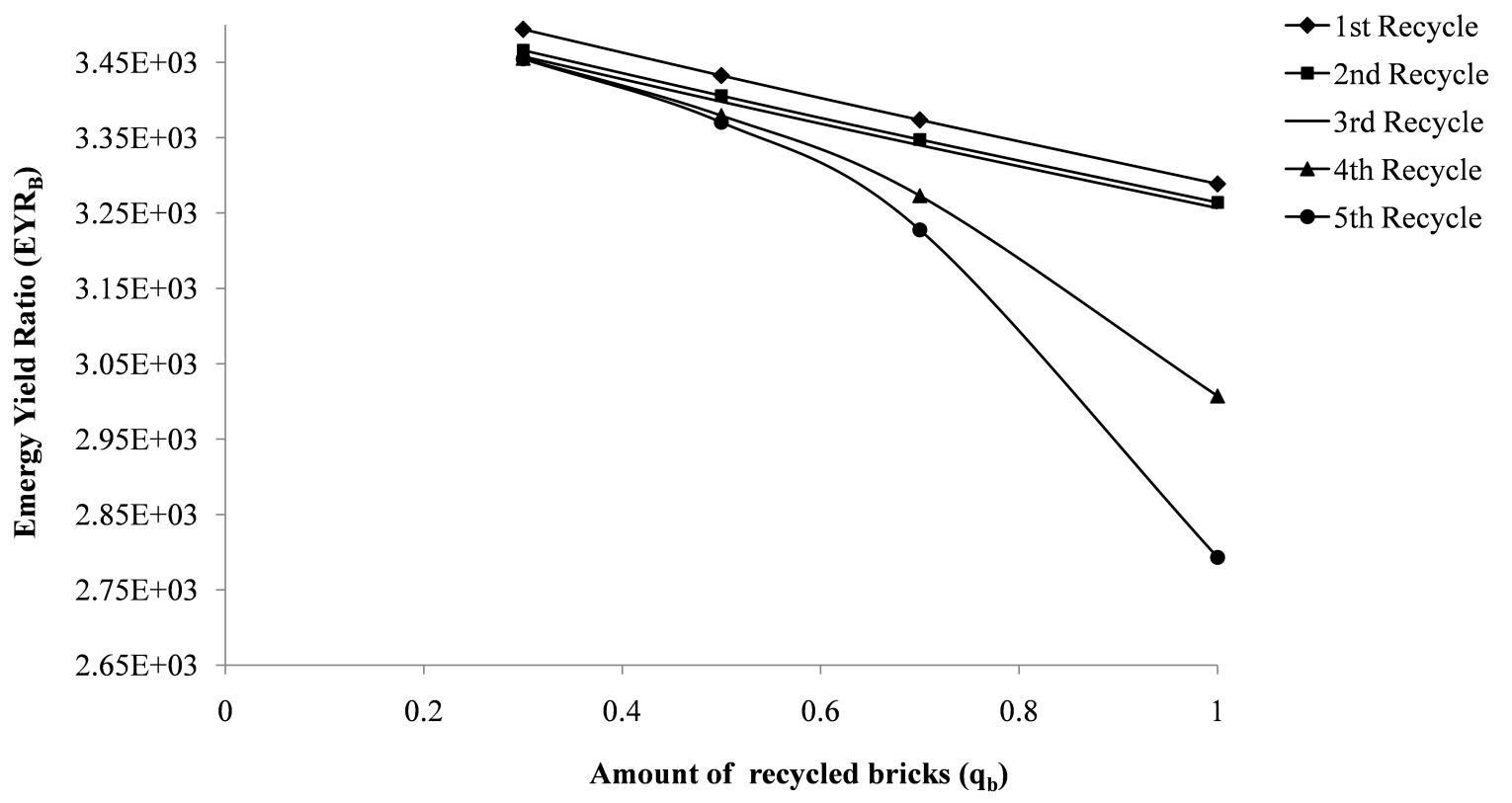


Figure 4b

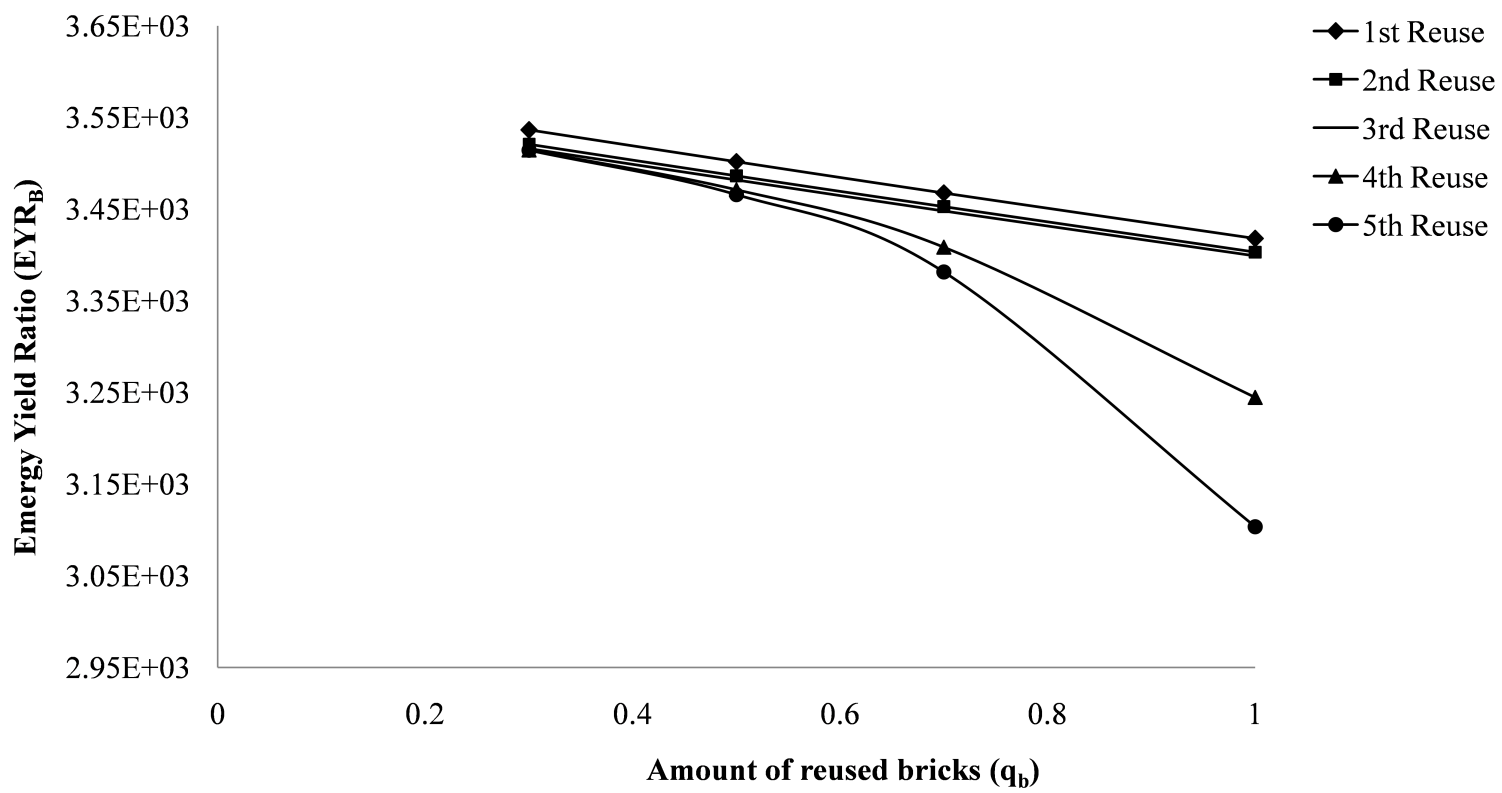


Figure 5

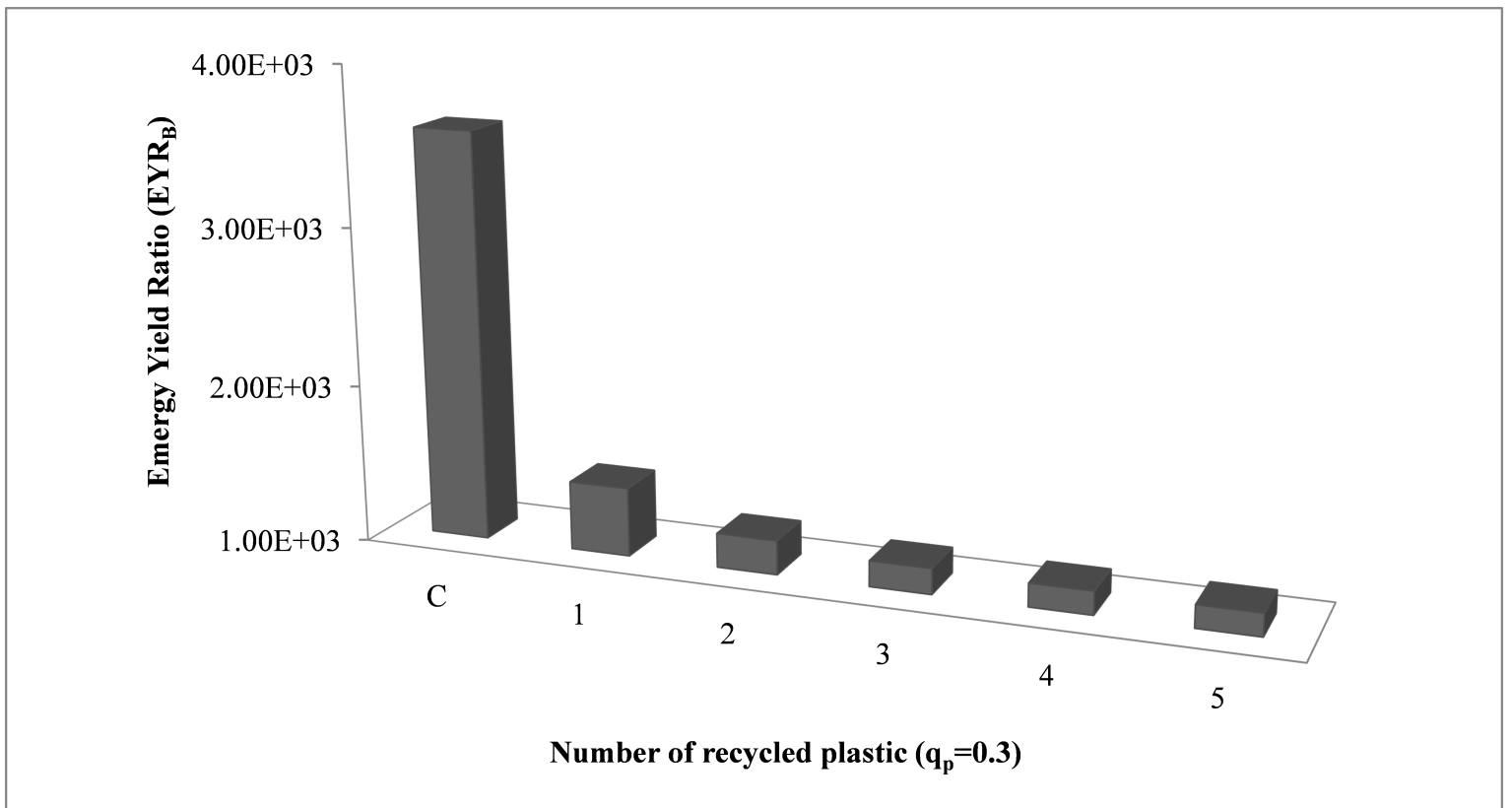


Figure 6

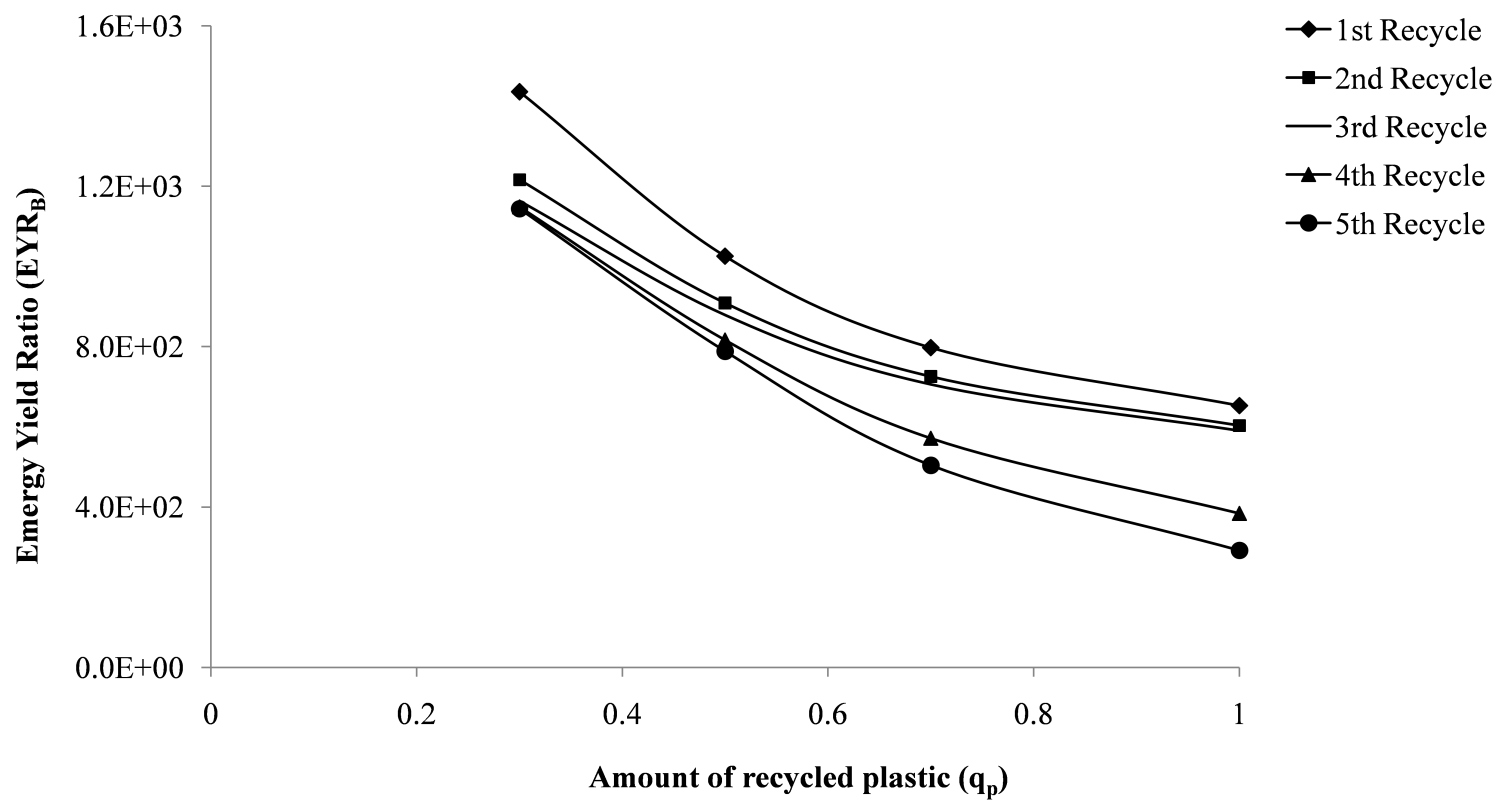


Figure 7a

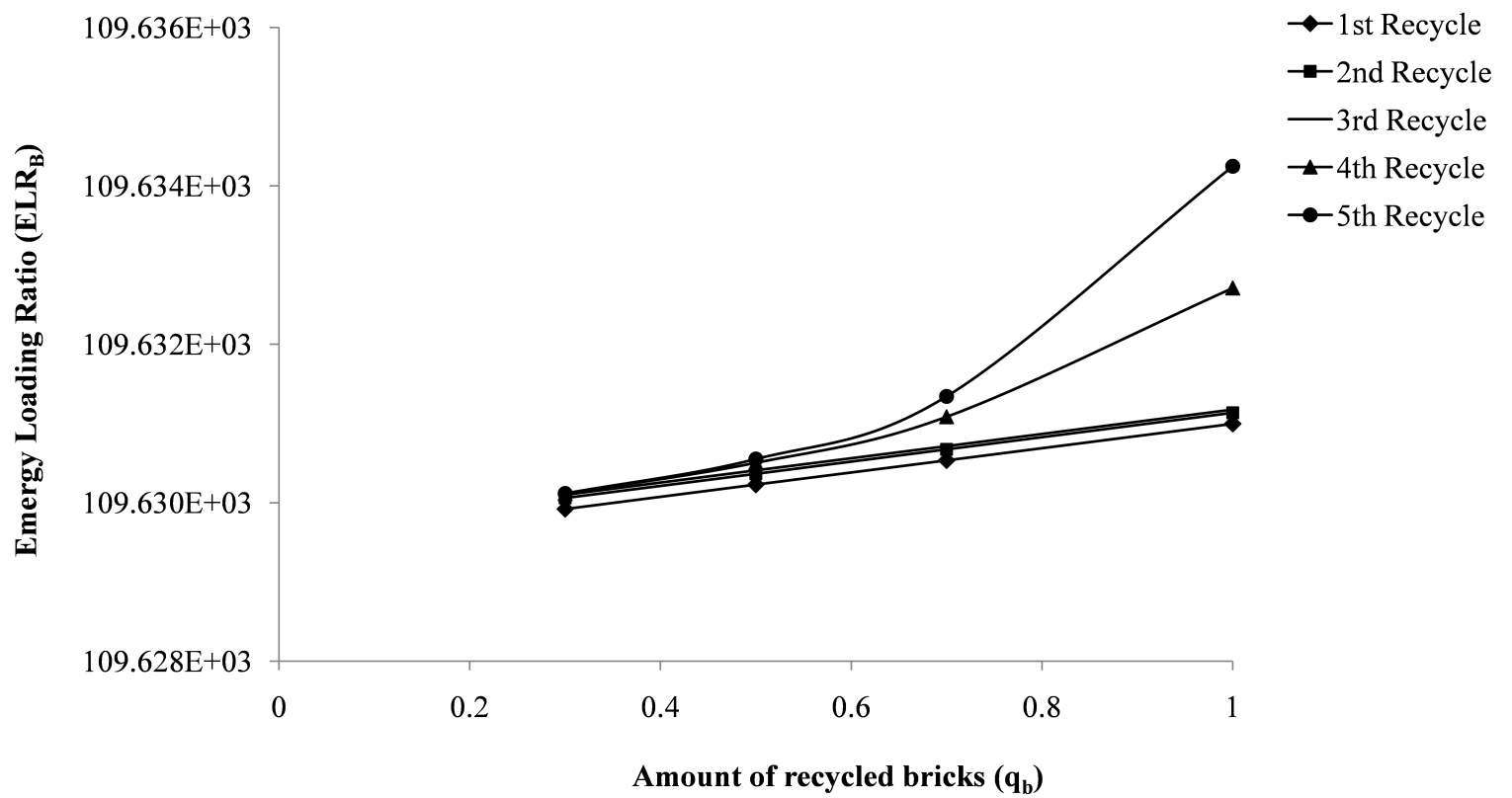


Figure 7b

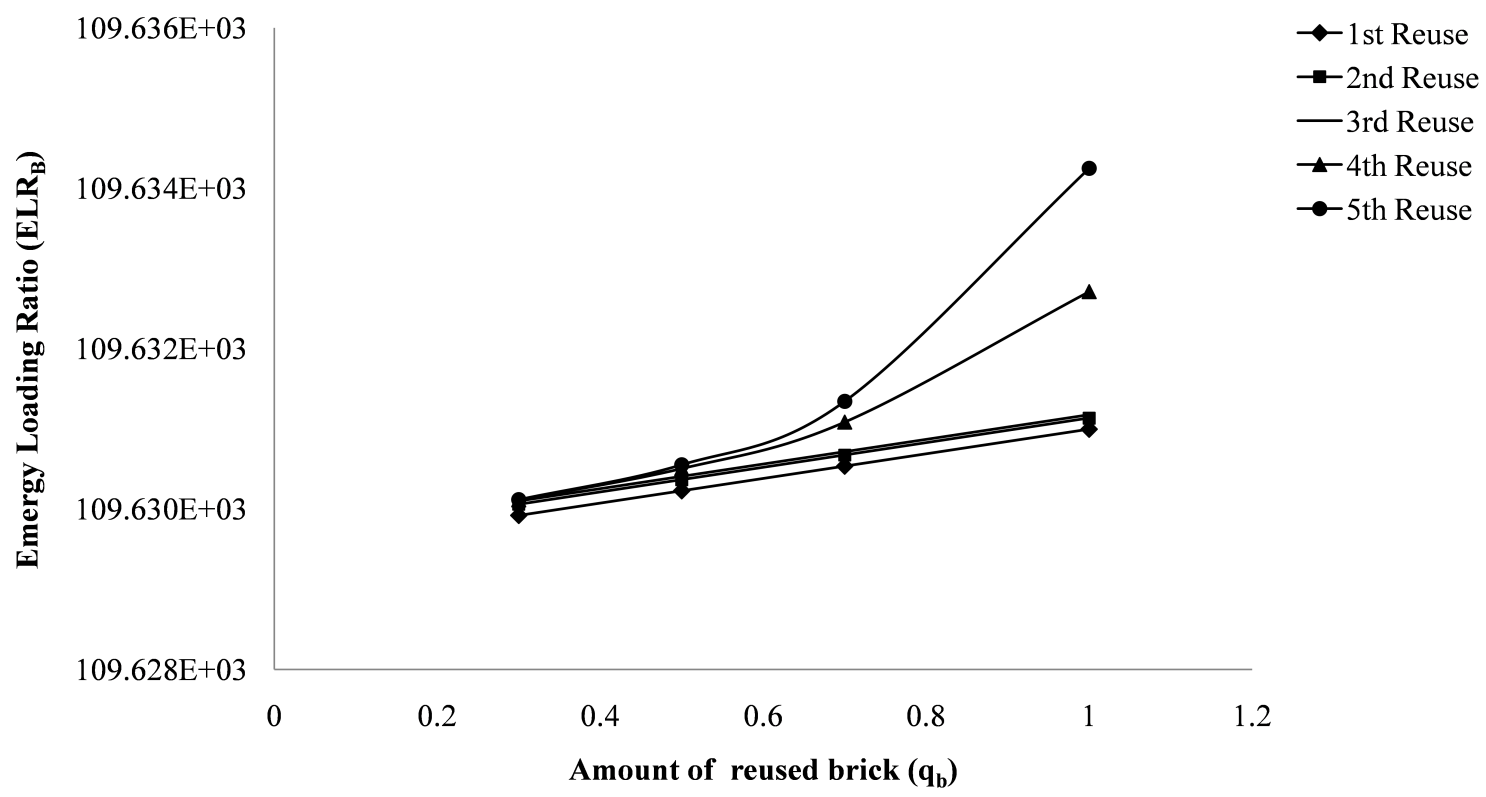


Table1

1 Note	2 Item	Density (kg/m <sup>3</sup> )	Volume (m <sup>3</sup> )	3 Raw data	Unit	4 Transformity (seJ/unit)	5 Ref.	6 Energy (seJ)
	<b>Renewable Inputs</b>							
1	Sun			6.19E+11	J	1.00E+00	a	6.19E+11
2	water	1000	614.52	6.15E+05	kg	4.80E+04	a	2.95E+10
	<b>Non Renewable Inputs</b>							
	Basement (floor)							
3	concrete	1500	5.1	7718	kg	1.81E+12	b	1.40E+16
4	Soft limestone	1500	1.0	1544	kg	1.68E+09	f	2.59E+12
5	Heavy concrete	2300	0.5	1183	kg	1.81E+12	b	2.14E+15
	Ground floor (floor)							
6	concrete	1300	0.8	1071	kg	1.81E+12	b	1.94E+15
7	heavy concrete	2300	0.2	474	kg	1.81E+12	b	8.58E+14
8	Polyurethane effisol	35	0.3	11	kg	8.85E+12	c	9.57E+13
9	Mortar	2000	0.3	618	kg	3.31E+12	c	2.05E+15
10	Tiles	2300	0.1	118	kg	3.68E+12	c	4.36E+14
	Underground Wall							
11	Concrete	1500	5.2	7803	kg	1.81E+12	b	1.41E+16
12	Heavy concrete	2300	1.0	2393	kg	1.81E+12	b	4.33E+15
	Wall (on the west)							
13	Light wood	500	0.2	110	kg	2.40E+12	f	2.64E+14
14	Wooden fibre	40	0.6	23	kg	2.40E+12	f	5.64E+13
15	Bricks	741	2.8	2040	kg	3.68E+12	c	7.51E+15
16	Plaster	1400	0.1	206	kg	3.29E+12	d	6.76E+14
17	Wooden panel	120	0.02	2	kg	2.40E+12	f	5.74E+12
18	plaster	1200	0.02	24	kg	3.29E+12	d	7.87E+13
	Wall coating							
19	Lime plaster	1400	0.1	73	kg	3.29E+12	d	2.41E+14
20	Bricks	741	1.0	727	kg	3.68E+12	c	2.67E+15
21	Plaster	1400	0.1	73	kg	3.29E+12	d	2.41E+14
	Plastering							
22	Plaster	1400	0.01	14	kg	3.29E+12	d	4.68E+13
23	Concrete blocks	1300	0.10	132	kg	1.81E+12	b	2.39E+14
24	Lime plaster	1400	0.01	14	kg	3.29E+12	d	4.68E+13
	Wall (East)							
25	Porothermn bricks30	762	0.3	196	kg	3.68E+12	c	7.21E+14
26	Bricks 10.7 cm	1700	0.1	153	kg	3.68E+12	c	5.63E+14
27	Bricks 10.5 cm	1700	0.1	153	kg	3.68E+12	c	5.63E+14
	Wall (North)							
28	Concrete	1500	1.8	2694	kg	1.81E+12	b	4.88E+15
29	Bricks	741	0.7	499	kg	3.68E+12	c	1.84E+15
30	Wooden fibre	40	0.1	3	kg	2.40E+12	f	6.90E+12
31	Light wood	500	0.1	27	kg	2.40E+12	f	6.47E+13
	Intermediate Floor							
32	Plaster	1500	0.1	154	kg	3.29E+12	d	5.07E+14
33	Concrete	1300	0.6	802	kg	1.81E+12	b	1.45E+15
34	Heavy concrete	2300	0.2	473	kg	1.81E+12	b	8.56E+14
35	Polystyrene extrude	35	0.3	11	kg	8.85E+12	c	9.55E+13
36	Mortar	2000	0.3	514	kg	3.31E+12	c	1.70E+15
37	Tiles	2300	0.1	118	kg	3.68E+12	c	4.35E+14
	Room Partitioning							
38	Plaster	1200	0.1	74	kg	3.29E+12	d	2.44E+14
39	Wooden fibre	40	0.5	20	kg	2.40E+12	b	4.75E+13
40	Plaster+cellulose	1200	0.1	74	kg	3.29E+12	d	2.44E+14
41	Concrete	600	0.1	73	kg	1.81E+12	b	1.33E+14
	Roof rafters							
42	Terracotta	1900	0.1	153	kg	1.68E+09	b	2.57E+11
43	Air space	1	0.0	0.04	kg	6.97E+12	a	2.80E+11
44	Wooden fibre	40	0.5	19	kg	2.40E+12	b	4.63E+13
45	Wooden board	800	0.1	43	kg	2.40E+12	b	1.03E+14

1 Note	2 Item	Density (kg/m <sup>3</sup> )	Volume (m <sup>3</sup> )	3 Raw data	Unit	4 Transformity (seJ/unit)	5 Ref.	6 Emergy (seJ)
	Upstairs Roofing							
46	Terracotta	1900	0.1	165	kg	1.68E+09	b	2.78E+11
47	Air space > 1.3 cm	1	0.0	0.04	kg	6.97E+12	a	3.03E+11
48	Wooden fibre	40	0.5	21	kg	2.40E+12	b	5.01E+13
49	Light wood	800	0.1	46	kg	2.40E+12	b	1.11E+14
50	Interior wooden door	750	0.06	48	kg	2.40E+12	b	1.15E+14
60	Double glass window for external door 4,16,4 argon	2700	0.03	82	kg	2.13E+13	c	1.74E+15
61	Glass Window	2700	0.02	44	kg	1.41E+12	e	6.18E+13
62	External wooden door	750	0.06	41	kg	2.40E+12	b	9.91E+13
63	metallic gate	7874	0.01	48	kg	8.55E+08	a	4.12E+10
64	Drainage system (PVC)			171	kg	9.86E+12	c	1.69E+15
65	Staircase (wood)			300	kg	2.40E+12	b	7.20E+14
	<i>Purchased Inputs</i>							
66	Fuel (Transports)			1.74E+08	J	1.13E+05	h	1.96E+13
	<i>Energy consumed (Electricity use on site)</i>							
67	Nuclear (78%)			8.88E+05	J	2.00E+05	g	1.78E+11
68	Hydro (14%)			1.59E+05	J	8.00E+04	a	1.28E+10
69	Natural gas (4%)			4.56E+04	J	4.80E+04	a	2.19E+09
70	Coal (4%)			4.56E+04	J	4.00E+04	a	1.82E+09
	Total emergy for building manufacturing							7.11E+16

[a] Odum et al. (2000); [b] Simoncini (2006); [c] Brown and Buranakarn (2003); [d] Meillaud et al. (2005); [e] Odum et al. (1987); [f] Odum (1996); [g] Brown and Arding (1991); [h] Bastianoni et al. (2005)

Table 1. Emergy evaluation Table



**Table 2**

	$\psi E_c, \text{ seJ}$
<b>Recycling</b>	
1st	5.4E+11
2nd	7.1E+11
3rd	7.6E+11
4th	7.7E+11
5th	7.8E+11

Table 2. Results of bricks recycling for different number of recycling times

**Table 3**

	Difference with initial energy seJ
<b>Reuse</b>	
1st	2.99E+11
2nd	3.89E+11
3rd	4.15E+11
4th	4.24E+11
5th	4.26E+11

Table 3. Results of new energy of building for reuse of bricks (e.g. in concrete mix)