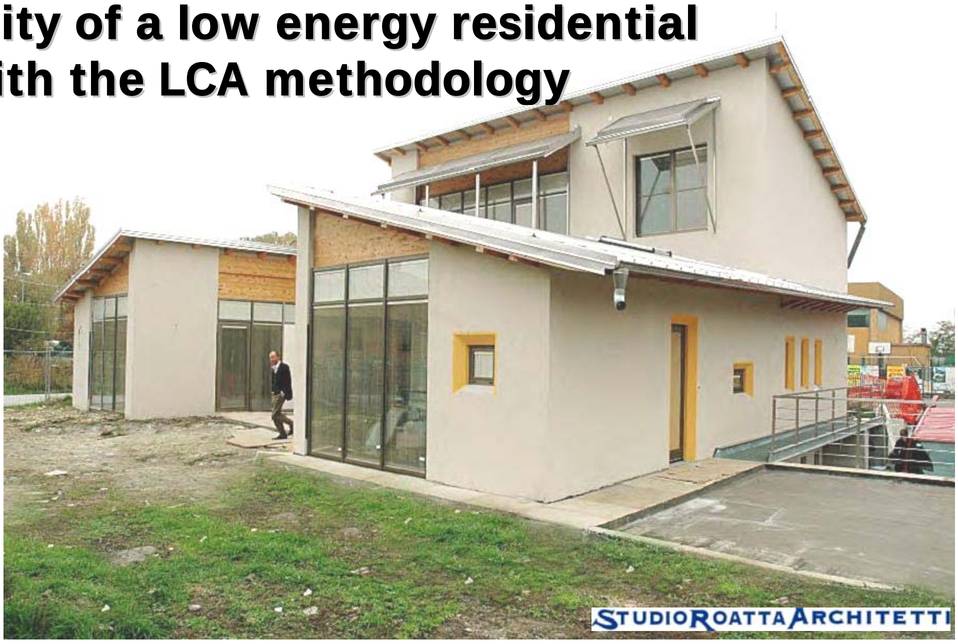
POLITECNICO DI TORINO - DITAG
Dipartimento di Ingegneria del Territorio
dell'Ambiente e delle Geotecnologie

SAM2 ARCELOR Seminar

2nd International Seminar on Society and Materials

# Evaluation of the environmental sustainability of a low energy residential building with the LCA methodology



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*SAM2*
*24-25 April 2008, Nantes, France*

*Ecole des Mines de Nantes*

*La Chantrerie*
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Please cite this article as:

Blengini G.A., Di Carlo T. (2008) Evaluation of the environmental sustainability of a low energy residential building with the LCA methodology. In Proc. Conf. SAM2 2008, Nantes, France, April 24-25, 2008, available on-line (July 2008) at http://www.emn.fr/x-ener/sam2/

# Evaluation of the environmental sustainability of a low energy residential building with the LCA methodology

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## ABSTRACT

A detailed case study Life Cycle Assessment (LCA) was conducted of a single unit low energy residential building located in northern Italy. As the house was designed with the objective of lowering the winter heat requirement to one tenth of a standard building according to the most restrictive Italian regulations, the overall objective of the research was to understand the energy and environmental benefits in a life cycle perspective. The study confirmed that the overall goals of sustainability were reached, but with a lower extent. The contribution analysis showed that embodied environmental burdens are higher than those relevant to the use-phase and the recycling potential plays a remarkable role, thus confirming the need of LCA to carefully assess sustainability of low energy buildings.

**Keywords**: LCA, building sustainability, energy saving, recycling potential

## INTRODUCTION

During the last decades, lowering energy use and the environmental impacts of building has increasingly become a priority in both European and Member States environmental policies. In the case of Italy, especially in the northern part of the country, such policies have extensively been integrated in the local building regulations mainly through direct and indirect actions aimed at decreasing the energy requirement for winter heating.

However, although it is well known that the use phase firmly remains the most important contributor to the life cycle impacts of existing building assets [Sartori et al. 2007; Blengini 2008], interest in understanding energy use, the consumption of natural resources and pollutant emissions in a life cycle perspective is growing, as reported in a number of previous studies [Adalberth et al 2007; Maddox et al. 2003; Blanchard et al.1998; Huberman et al.2008; Chen et al.2001]. In order to really appraise the overall environmental impacts of buildings, all the life cycle should in fact be encompassed by also including the embodied energy and environmental interventions related to the materials, construction activities, dismantling operations and the end-of-life.

The overall judgement relevant to the building sustainability must in fact encompass all the life phases and should be carried out by using an objective and internationally recognised methodology such as Life Cycle Assessment (LCA), according to the ISO 14040 standard.

The Rapporto Energia e Ambiente 2005 issued by ENEA has in fact reported that the use phase of buildings in Italy roughly corresponds to 31% of the final energy use and 31% of greenhouse emissions throughout the country in the year 2004. However, when using the life cycle approach, therefore including the manufacturing of construction materials (cement, bricks, glass, ceramics, etc.) and considering building activities, the final energy use rises to 37% and greenhouse emissions to 41%.

The research started from an analysis of the international LCA literature [Sartori 2007; Huberman et al.2008; Blengini 2008] according to which the building operational phase is responsible for 90-95% of the life cycle impacts. However, although in case of a conventional building the relative contribution of embodied environmental burdens is minor to negligible, when dealing with a low energy building, the relative importance of the pre-use and use phases is reversed. In that case, according to Huberman et al. [2008] the embodied energy rises up to 60%.

Based on these preliminary considerations, the paper presents the results of a research programme focused on the LCA of a low energy single unit residential building, located in Morozzo, Piedmont-Italy (Fig. 1). The building was designed and recently erected (end of 2007) in order to achieve an overall goal of energy saving well behind the most restrictive Italian legislative prescriptions: one tenth of the maximum winter heat requirement allowed for a standard building.

The overall objective of the research was to understand whether and to what extent the environmental benefits obtained by having drastically lowered the energy requirement for winter heating and sanitary water production could be confirmed in a life cycle perspective. Low energy buildings are typically characterised by higher embodied environmental burdens that might reduce, or even cancel, the achieved environmental benefits.

With that in mind, a detailed LCA model was carried out in compliance with Guinée's definition [Guinée 2002] relevant to the Morozzo's house. For comparison, a second LCA model was carried out, relevant to the same house, but with standard winter energy requirement performances. Detailed and quantitative field measured data on materials embodied in the building shell and fixtures, as well as using primary data relevant to the construction phase were used. As the demolition and waste material recycling processes have seldom been addressed in previous LCA studies [Adalberth et al.2001; Chen et al. 2008; Blengini 2008], in some cases being excluded [Huberman et al.2008] and often being modelled using literature data [Sartori et al 2007; Thomark 2006], a further specific objective was to expand the LCA model by including a realistic end-of-life scenario for the most important building materials. Thus, taking into account the knowledge gathered in previous LCA research focused on end-of-life of building materials [Blengini 2008] and considering the recycling potentials, as defined by Thormark [2002], the suitability and the importance of adopting appropriate *design for dismantling* solutions were addressed.

## METHODOLOGY

To obtain a comprehensive energetic and environmental picture relevant to the low energy building under study, the Life Cycle Assessment (LCA) methodology has been used, according to the four major stages described in the ISO 14040: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation.

As far as the Impact Assessment step is concerned, the analysis was run at two levels.

The LCIA phase was initially focused on the characterisation step, highlighting the life cycle energy use and greenhouse emissions, as they are usually considered topical issues in the building sector. The following indicators were thus considered: GER (Gross Energy Requirement) as an indicator relevant to the total primary energy consumption (direct + indirect + feedstock) according to Boustead and Hancock [1979]; GWP100 (Global Warming Potential) as an indicator relevant to the greenhouse effect [IPCC 1996].

As a second level of the LCIA step, although it must be remarked that there is neither consensus on weighting [Huberman et al.2008; Badino et al.1998; Georgakellos 2006; Scheuer et al. 2003; Boustead et al.2000], nor on the best weighting method to adopt, the Eco-Indicator 99 method [Goedkoop et al.1999] was also used in order to express a more comprehensive environmental judgment over a wider range of environmental aspects, including human health, ecosystem quality and resource use.

SimaPro 7 software application was used as supporting tool in order to implement the LCA model and carry out the assessment.

## STUDIED OBJECT

The low energy residential building (Morozzo's house – Fig. 1) was designed by Studio Roatta Architets in Mondovì-italy with the objective of lowering the winter heat requirement to 10.38 kWh/m$^2$ per year, exploiting as much as possible passive solar contributions, optimizing thermal insulation and minimizing uncontrolled inward air flows.

The standard house mirrors the original in size features and geographical/climatic conditions of the Morozzo's house (Fig. 1). Energy consumption for heating was recalculated in compliance with the legislative requirements (Decree 192/2005 subsequently amended by legislative decree 311/2006, valid from February 2007) and consequently the building shell and the building appliances were adapted.

**Geographical data: Morozzo (CN), Piedmont , northern italy**

| Altitude | Latitude | Longitude | Degree Days | Climatic area | Conventional heating period |
|---|---|---|---|---|---|
| **431 m** | **44°25' north** | **7°42' east** | **2850** | **E** | **183 days** |

*Figure 1: the low energy building under study (the Morozzo's house)*

### 1. Functional unit and System Boundaries

In accordance with previous LCA research [Adalberth, 2001; Blengini 2008], the choice of the functional unit is arbitrary, but, for comparison purposes, a standardisation might be helpful. All this considering the adopted functional unit was 1 m$^2$ net floor area over a period of 1 year. The net area (250 m$^2$) was calculated as the sum of the living area plus 1/3 of the garage area.

System boundaries includes: raw materials extraction; manufacturing and transportation of building materials; erection of the building envelope; use of the building for a period of 70 years; demolition of the building, operation of recycling/treatment of the rubble. The study can be therefore defined as a from-cradle-to-grave LCA.

Inventory data for the LCA model were retrieved from different database included in the SimaPro software package (Ecoinvent, Idemat 2001 and Buwal 250 databases).

## 2. Inventory of the Morozzo's Low Energy House (LEH)

A description of the main inventoried elements is given in the following paragraphs.

### a. Pre-use phase

The pre-use phase includes all that concerns the production of the building materials and the erection of the building.

The inventory data were either field measured data or data estimated from original building drawings. Data are mainly referred to:

1. quantities of embodied materials, their relative construction waste factors during building erection and the repair/replacement factors;
2. transportation of materials from manufacturing site to construction site;
3. energy consumption relevant to the use of machinery during the construction phase.

The LCA model of the building under study has been divided into two systems: one relevant to the building shell, subdivided into ten subsystems, and a second one relevant to plants and fixtures, including electric, heating, ventilation and water plants (Table 2).

*Table 1: Inventoried building systems and subsystems*

| BUILDING SHELL | MAIN MATERIALS (life span: 70 years) |
|---|---|
| **Basement** | Cement; Concrete and Steel bars; PET |
| **Garage area** | Concrete and Steel bars; Cement; Bricks; Mortar |
| **Floors and stairs** | Concrete and Steel bars; Steel |
| **Structural walls** | Bricks and Mortar; Concrete and Steel bars |
| **Interior walls** | Gypsum, Steel, Wood wool |
| **Roof** | Wood; Sawn timber, Particle board; Kraft paper; Wood wool; Aluminium |
| **Terrace** | Zinc coated steel ; Wood |
| **Windows and doors** | Alluminium; HDPE; Wood; Glass; Polystyrene; Steel |
| **Wall surface lining** | Cement and Lime Mortar; Polystyrene Acrylic varnish; Cork slab; Ceramic tiles |
| **Flooring** | Cement; Ceramics; Stoneware |
| **PLANTS & FIXTURES** | **MAIN MATERIALS (life span: 35 years)** |
| **Water plant** | HDPE (Drainage piping); HDPE and Alluminium (potable water pipes); Chromium Steel (rain water pipes); Sanitay ceramics, steel, glass; Brass and PVC (bathroom accessories); Alluminium, Mineral wool, Copper, Glass (for solar panels) |
| **HVAC/heating** | Steel tank; Polyetylene; Aluzinc (heating pump) |
| **Lighting** | Copper, PVC and HDPE |
| **Ventilating** | HDPE; Aluzinc |

Figure 2 shows an overview of the inventoried building materials: concrete is the main constituent of the building shell, representing 66% in mass, followed by other lithoid materials (cement, bricks).

As it can be seen in Figure 2, the average composition of plants and fixtures is much more variable than the composition of shell materials.

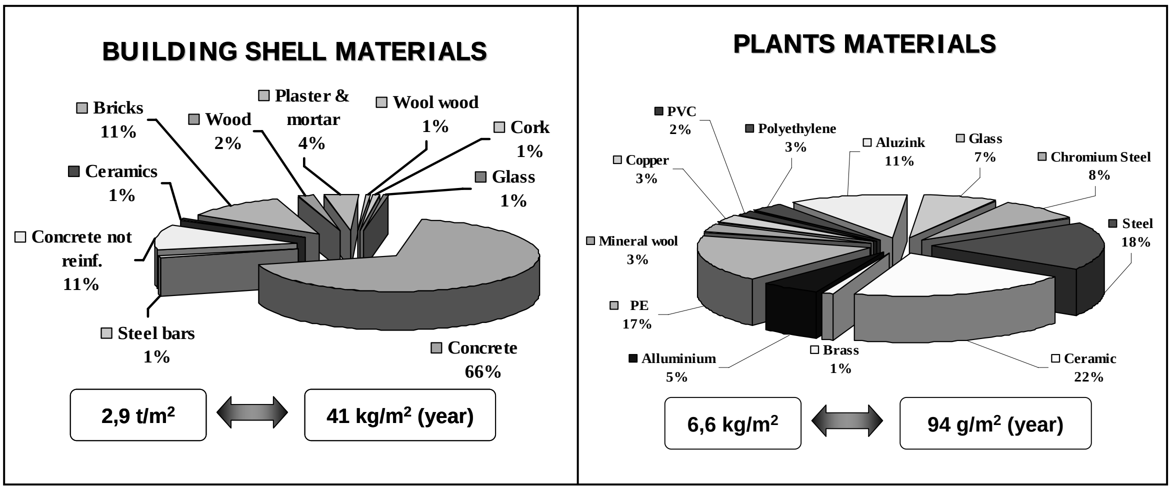

*Figure 2: Materials involved in the building shell and in plants & fixtures*

b. Use phase

The energy consumption during the operational phase, was calculated by making a distinction between uses which depends from the house size (heating and ventilating) and the ones depending from the number of occupants (sanitary water, cooking, lighting, appliance use).

Annual energy demand for heating and ventilating were calculated by the designers according to the architectural and thermo-phisical features, as well as the local climate conditions, by using the software EDILCLIMA [EC501(L. 10/91)vers. 6]. A heat pump system with a COP of 2.54 and a average global seasonal yield (inclusive of regulating and distributing) of $\eta G,s=2.62$ was included in the LCA model. The energy requirement for hot water production was calculated considering a number of 4 occupants and a 50 l daily demand. A solar panel system supplies 95% of the yearly energy requirement.

Basic information on energy used for cooking and lighting was retrived from official statistics [ENEA 2005; Piano Energetico della Provincia di Torino 1997].

All the activities related to the operational phase of the house, over the 70 year lifespan, are supposed to be powered by electricity according to the Italian mix (Table 2).

*Table 2 : Energy consumption during the use phase of the LEH*

| Energy consumption | | |
|---|---|---|
| Heating & Ventilating | 4.7 | kWh/m$^2$,year |
| Sanitary water supply | 22.8 | kWh/year |
| Cooking | 542.5 | |
| Lighting and use of appliances | 1646 | |

c. End-of-life phase

Three distinct subsystems are included in the LCA model for the end-of-life phase:

1. Selective dismantling for materials and reusable/recyclable structures (windows, steel, aluminium, wood).
2. Controlled demolition of the concrete structure by hydraulic hammers and shears.
3. Operations for rubble treatment and subsequent recycling. The lithoid fraction was supposed to undergo a recycling process for the production of secondary aggregates. As far as the LCA model is concerned, the production of recycled aggregates was considered as an avoided impact equal to the environmental burdens associated with the displaced natu-

ral aggregates. Aluminium, steel, glass and copper were supposed to undergo an average recycling process according to the most likely end-of-life scenario outlined in previous LCA studies [Blengini 2008] and according to the recycling processes available in the Buwal 250 database.

All the energy consumption and environmental impacts due to transportation, demolition and recycling operations were considered in the inventory analysis. Therefore, the net environmental benefits from demolition and recycling have been accounted for.

## 3. Inventory of the Standard house (SH)

The main differences between the SH and the LEH are those relevant to the thickness and type of insulation and the total glazed surface which is reduced in the standard house. The table 3 summarizes the changes in the structural subsystem.

*Table 3: Changes in the standard house structural subsystem*

| Structural subsystem | Variations | Notes |
|---|---|---|
| **Roof** | Wood wool substituted with polystyrene and decrease thickness | From 22 cm to 5 cm |
| | Excluded OSB panel | |
| **Surface lining** | Cork slab substituted with polystyrene of decreased thickness | from 15 cm to 4 cm |
| | Included polystyrene to support heating piping floor system | thickness 3 cm |
| | Excluded polystyrene from garage ceiling area | |
| **Windows** | Triple glass substituted with double glass and total glazed surface decreased | From 100 $m^2$ to 35 $m^2$ |
| | Decreased total aluminium for windows frames | |
| **Exterior walls** | Increased total bricks quantity consequently to the increasing glazed area | Added 11 t |

The most important changes relevant to plants and fixtures, are mainly due to the exclusion of solar panels and the ventilation system, the exclusion of the hot water tank and the increase of pipelines for the heating system by a factor of 4. Taking into account the new building features, the energy requirement has been re-calculated using the same EDILCLIMA software. Heating, sanitary water supply and cooking were powered by natural gas. Energy requirement for lighting and use of appliances remained unchanged.

Table 4 summarizes the variations of energy requirements for the standard house.

*Table 4: Changes in the energy requirement from LEH to SH*

| Energy use | Energy source | Variation |
|---|---|---|
| **Heating** | From electricity to natural gas | from 10,38* kWh $m^2$,year → 109,5* kWh $m^2$,year |
| **Sanitary water** | From electricity to natural gas | from 248* MJ/house.,year → 10670* MJ/ house.,year |
| **Washing** | Electricity | from 150** kWh house.,year → 300** kWh house.,year |
| **Cooking** | From electricity to natural gas | from 542,5** kWh house.,year → 774,6** kWh ab.,year |
| | | ** heat requirement      ** end use energy* |

The end-of-life phase remained the same as the one already described for the low energy house.

## RESULTS AND DISCUSSION

Figures 3 and 4 show the achieved results relevant to the life cycle of the low energy house under study, in comparison with the standard house and with reference to the adopted functional unit (1m$^2$, year).

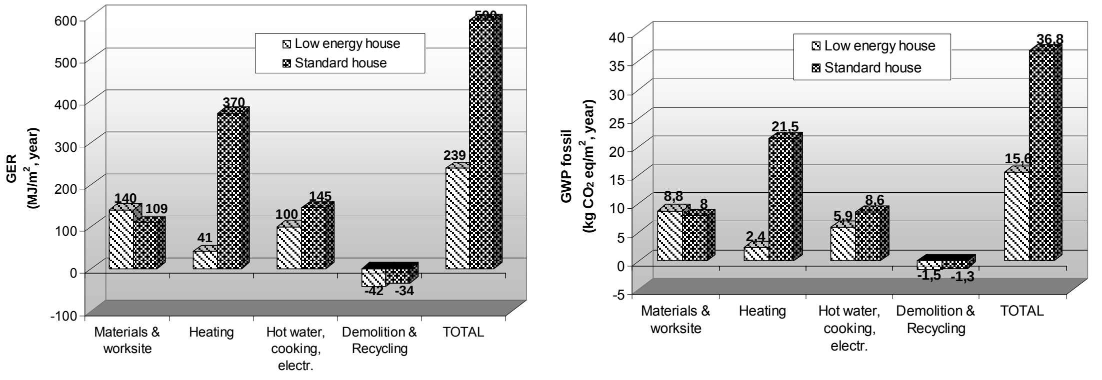

*Figure 3: Life cycle impacts relevant to energy (GER) end greenhouse emissions (GWP)*

The contribution analysis and the comparison between the LEH and the SH can be helpful to highlight the role and significance of the different subsystems in a life cycle perspective.

The total life cycle energy consumption is 590 MJ/m$^2$per year for the SH, while it is 239 MJ/m$^2$ per year, for the LEH.

While in the standard house the use phase is responsible for 87% of the life cycle energy use, in case of the LEH the contribution of the use phase virtually corresponds to the contribution of the pre-use phase.

As it can easily be seen in Figure 3 and Figure 4, similar achievements were obtained also for the GWP and the Ecoindicator 99.

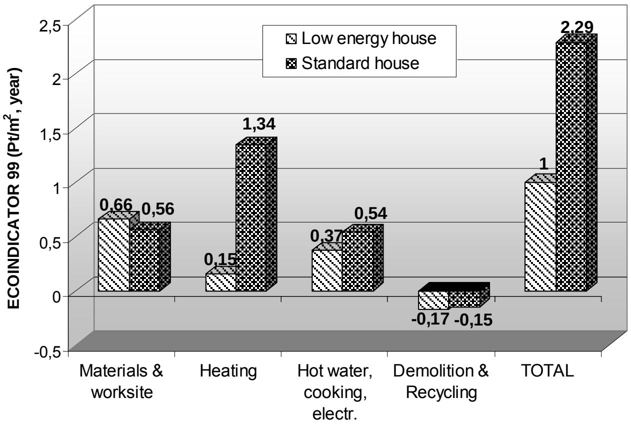

*Figure 4: Life cycle impacts relevant to Ecoindicator 99*

These results clearly overturn the weight and significance of the pre-use and use phases, putting into evidence that the contribution of embodied energy and environmental burdens cannot be neglected when dealing with energy saving and sustainability issues relevant to low energy buildings.

In such a context, it becomes clear that LCA can represent a very interesting and powerful assessing and eco-design tool.

According to Figure 5, materials embodied in the building shell account for 95% of energy consumption (GER) in the pre-use phase, while the operations for the building construction account for 5% only.

The most important contributor to energy use in the pre-use phase is wood (sawn timber, particle board, wood wool, cork slab). However, it must be remarked that 76% is ascribable to renewable energy. Ceramics have the second largest contribution to the GER and concrete has the main contribution to GWP.

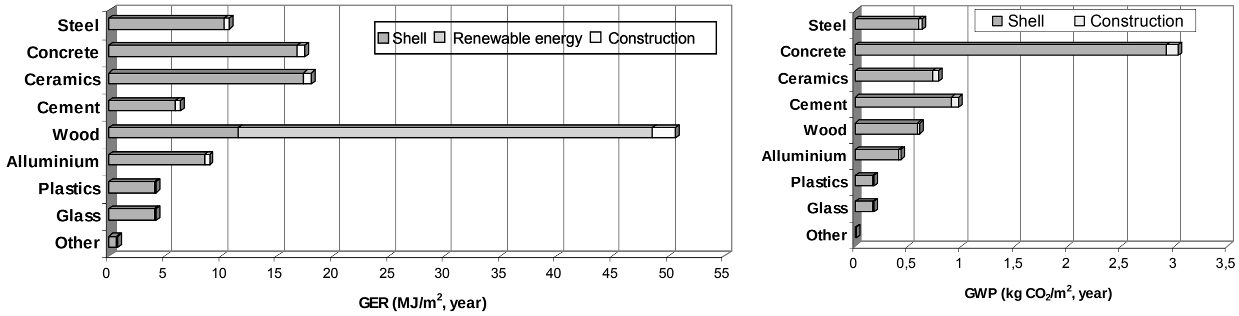

*Figure 5: Contribution of materials embodied in the building shell to the impacts of the pre-use phase (LEH)*

When making a distinction between shell and fixtures materials, it has been remarked that the last ones account for only 10% of pre-use phase energy consumption.

Among structural subsystems, roof (12% of life cycle GER) and wall surface lining (10.6% of life cycle GER) are the major contributors to energy use. Among plants and fixtures the most important contributor is the water supply plant (3.1% of life cycle GER).

A very important issue is that relevant to the recycling potential of building materials: the net environmental saving in comparison to the embodied environmental burdens [Blengini 2008].

Thus, the LCA model of the low energy building showed a recycling potential of 30% in terms of GER, 17% in terms of GWP and 27% in terms of Ecoindicator 99.

Therefore, the proper end-of-life management, as a consequence of the correct choice of building materials and the proper recycling processes, can be useful to lower the life cycle impacts. Moreover, as remarked in previous studies [Huberman et al.2008; Thomark 2002], the more energy needed during the use phase decreases, the more important it is to pay attention to both energy for material production and to the aspects of the recycling potential.

A deeper comparison between the low energy and the standard houses has highlighted some very interesting aspects. The winter heat requirement has drastically been reduced from 109 to 10 kWk/m$^2$, which roughly corresponds to one tenth of the heat requirement of a standard building (10 to 1).

When considering the overall efficiency of the heat pump/electricity and boiler/natural gas energy chains, in a from-cradle-to-gate perspective, the ratio between LEH and SH, in terms of gross energy requirement (GER), roughly remains unchanged (10 to 1).

However, when considering the whole building use-phase, therefore adding sanitary water, cooking, lighting and use of appliances, the ratio between LEH and SH changes to 3.7 to 1.

Moreover, when considering the full life cycle, the ratio becomes 2.5 to 1 in terms of GER, 2.4 to 1 in terms of GWP and 2.3 to 1 in terms of Ecoindicator 99.

## FINAL CONCLUSIONS

The results of a detailed LCA application to a low energy single house in Morozzo-Italy highlighted that the role and significance of all the life cycle phases and subsystems should carefully be re-considered, when dealing with energy saving and sustainability issues relevant to low energy buildings.

It has been remarked that in the life cycle of the low energy building under study, the use of a single electric appliance like the refrigerator or the ironing board, whose influence could be neglected in case of a standard building, can play a significant role. Similar remarks can describe the role of building materials, whose life cycle contribution cannot be neglected anymore. Moreover, the recycling potential can become an effective tool to further lower the life cycle impacts of the whole building.

As a major conclusion of the research, the overall goal of environmental sustainability behind the construction of Morozzo's house was reached and it has proved to be consistent with the life cycle approach. The higher embodied burdens of the low energy building were compensated by the remarkable operational energy saving. However, the LCA has shown that while the Morozzo's house winter heat requirement is reduced to 1/10, the life cycle impacts are only reduced to 1/2.3 to 1/2.5, depending on the life cycle indicator.

These results suggest to further use LCA to promptly verify any future attempt of improving the environmental performances of similar buildings, as single step improvements could not be effective in a life cycle perspective, or might even disappoint expectations.

## ACKNOWLEDGEMENTS

The authors would like to thank Studio Roatta Architects in Mondovì-italy for the data and information supplied, Msc. Agnese Fiorenza and Dr. Katia Zavaglia for their help in the data collection and elaboration and Professor Vanni Badino for his scientific supervision.

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