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LIFE CYCLE MANAGEMENT

Energy-saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy)

Gian Andrea Blengini · Tiziana Di Carlo

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Abstract
Background, aim and scope A low-energy family house recently built in Northern Italy was selected by Regione Piemonte as an outstanding example of resource efficient building. An economic incentive was awarded to cover the extra costs of the thermal insulation, windows and equipment in order to decrease the yearly winter heat requirement from the legal standard of 109 to 10 kW h/m^2, while existing buildings in the study area typically require 200 kW h/m^2. As the building was claimed to be sustainable on the basis of its outstanding energy-saving performance, an ex post life cycle assessment (LCA) was set up to understand whether, and to what extent, the positive judgement could be confirmed in a life cycle perspective.
Materials and methods After an analysis of the literature on LCA of whole buildings, a detailed life cycle assessment has been conducted by encompassing all the life cycle phases. Emphasis was given on the end-of-life stage, too often disregarded due to lack of data or heavily simplified. Virtually all the materials used in the building structure, finishes and equipment were considered, paying attention to their expected service duration and the recycling potential. In order to increase transparency and therefore credibility and acceptance of LCA in the building sector, an uncertainty analysis was carried out.
Results and discussion The dramatic contribution of material-related impacts emerged. Structure and finishes materials represented the highest relative contribution, but maintenance operations also played a major role. The contributions of equipment, construction stage and transportation were minor. The important role of the recycling potential also emerged. Unlike standard buildings, where heating-related impacts overshadow the rest of the life cycle, there is no single dominating item or aspect. Rather, several of them play equally important roles.
Conclusions The study confirmed that the initial goal of resource and environmental efficiency was reached, but to a much lower extent than previously thought. In comparison to a standard house, while the winter heat requirement was reduced from 109 to 10 kW h/m^2 (10:1 ratio), the life cycle energy was only reduced by 2.1:1 and the carbon footprint by 2.2:1.
Recommendations and perspectives The findings emphasise the need for incorporating the life cycle approach in energy-saving policies and economic incentives schemes in the building sector, in Italy and elsewhere, as single-step improvements might not be effective in a life cycle perspective and could even disappoint expectations.

Keywords End of life · Energy policies · LCA of whole buildings · Low-energy buildings · Recycling potential · Uncertainty analysis

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G. A. Blengini (✉)
Department of Production Systems and Business Economics,
Politecnico di Torino,
Corso Duca degli Abruzzi 24,
10129 Turin, Italy
e-mail: blengini@polito.it

G. A. Blengini
Institute of Environmental Geology and Geo-Engineering,
CNR-IGAG,
Corso Duca degli Abruzzi 24,
10129 Turin, Italy

T. Di Carlo
Department of Housing and City, Politecnico di Torino,
Corso Duca degli Abruzzi 24,
10129 Turin, Italy

1 Background, aim and scope

As acknowledged in the international literature, interest in understanding resource use and environmental implications of buildings in a life cycle perspective is rapidly growing. Life cycle impacts are highly interdependent, as one phase can influence the others. For instance, selection of building materials can help in reducing energy requirement for air conditioning, but it might also increase embodied energy and transport-related impacts or affect the service duration of the whole building, or even influence the generation of recyclable (or disposable) demolition waste at end of life (EOL).

While in some studies it has been confirmed that operation energy is by far the most important contributor to life cycle impacts of conventional buildings (Sartori and Hestnes 2007; Blengini 2009; Ortiz et al. 2009a; Blanchard and Reppe 1998; Scheuer et al. 2003; Adalberth et al. 2001), in some other cases (Chen et al. 2001; Mithraratne and Vale 2004; Citherlet and Defaux 2007; Huberman and Pearlmutter 2008; Junnila 2004) it has been pointed out that, especially for new and low-energy buildings, the relative weight of the remaining life cycle phases is sensibly more important. For instance, the embodied energy can contribute up to 40% of the life cycle energy according to Chen et al. (2001), up to 43% according to Mithraratne and Vale (2004) and up to 60% according to Huberman and Pearlmutter (2008). The lower the operation energy, the more important therefore is the adoption of a life cycle approach.

Lowering energy intensity of buildings is increasingly becoming a priority in energy policies in European countries. In Northern Italy, such policies are being integrated at different scales, from regional to local, mainly through direct and indirect actions aimed at decreasing operation energy, with focus on winter heating.

Although it is reasonable to tackle priorities starting from the most energy intensive elements, it should be pointed out that not only is the use phase a source of environmental concern but also the whole life cycle.

On the basis of these preliminary considerations, the paper presents the results of a detailed life cycle assessment (LCA) application to a low-energy single family house that has recently been built (end of 2007) in Northern Italy. The building, located in the town of Morozzo, in Piedmont, was designed with an overall energy-saving objective that is well beyond the most restrictive Italian national and local regulations: one tenth of the maximum winter heat requirement allowed for a standard building.

The house in Morozzo was selected by Regione Piemonte (the regional public administration) as an outstanding example of a very low-energy building. An economic incentive was awarded to cover the extra costs of the thermal insulation, windows and equipment to decrease the winter heat requirement from 109 to 10 kW h m^{-2} $year^{-1}$. Typically, existing buildings in the study area use 200 kW h/m^2.

As the building was claimed to be sustainable on the basis of its outstanding energy-saving performance, an ex post detailed LCA was carried out to understand whether, and to what extent, the benefits corresponding to the drastic reduction of operational energy could be confirmed in a life cycle perspective.

The LCA model of the low-energy house was compared with a second model relevant to the same house, but with standard winter energy requirement and conventional equipment (benchmark). In order to better understand the role and significance of life cycle phases and subsystems, field data were collected relevant to structure, finishes and equipment materials and the building process.

A literature survey on LCAs of whole buildings (Table 1) confirmed that there is limited availability of studies that extensively address building demolition and/or EOL of materials. Considering that in some cases EOL phase is excluded because of lack of data on demolition, recovery and recycling of materials (Ortiz et al. 2009a; Huberman and Pearlmutter 2008) or modelled with literature data and/or heavy simplifications (Scheuer et al. 2003; Adalberth et al. 2001; Chen et al. 2001; Citherlet and Defaux 2007; Junnila 2004; Thormark 2002; Peuportier 2001; Kofoworola and Gheewala 2008), special attention was paid to modelling a realistic post use scenario, taking into account the knowledge gathered in a previous study (Blengini 2009).

Due to the fact that the *design for disassembling* concept had not been adopted during the design process, only for some of the building materials was it reasonably possible to assume a selective disassembling and subsequent recycling or re-use. As a consequence, the recycling potentials, defined and discussed in previous studies (Thormark 2002; Blengini 2009), could be taken into account only for some materials, while for others, the only credible option was landfilling or incineration.

As Huijbregts et al. (2003) recommend evaluating uncertainties to increase transparency and therefore credibility and acceptance of LCAs, an uncertainty analysis was carried out. This should represent a further subject of interest, as published studies in the field of building LCA rarely report uncertainty (see Table 1).

The results of a LCA in the building sector should never be generalised, as they necessarily reflect the complex combination of the building unique features, locally adopted construction techniques, behavioural pattern of occupants and site-specific climate conditions. However, the methodology and the results here presented can be useful to address future LCA applications in the built environment.

Table 1 Overview of literature on LCA of whole buildings

Studies	Type of building	Structure materials	Equipment materials	Transportation	Construction stage	Maintenance	Use	End of life	Sensitivity analysis	Uncertainty analysis
[Present study]	R	X	X	X	X	X	X	X	-	X
Adalberth et al. 2001	R	X	X	X	X	X	X	X	X	-
Arena and Rosa 2003	S	X	-	-	-	-	X	-	X	-
Blanchard and Reppe 1998	R	X	X	X	X	X	X	-	X	-
Blengini 2009	R	X	-	X	X	X	X	X	X	-
Chen et al. 2001	R	X	-	X	X	X	X	X	-	-
Citherlet and Defaux 2007	R	X	-	X	X	X	X	X	-	-
Dewulf et al. 2009	R	X	-	X	X	X	X	X	-	-
Erlandsson and Levin 2005	R	X	X	-	-	X	X	-	-	-
Gerilla et al. 2007	R	X	-	X	-	X	X	X	X	-
Huberman and Pearlmutter 2008	S	X	-	X	X	X	X	-	-	-
Junnila 2004	O	X	X	X	X	X	X	X	-	-
Kofoworola and Gheewala 2008	O	X	-	X	X	X	X	X	-	-
Matasci 2006	R	X	X	X	X	X	X	X	X	-
Mithraratne and Vale 2004	R	X	X	X	X	X	X	-	-	-
Ortiz et al. 2009a	R	X	-	X	-	X	X	-	X	-
Peuportier 2001	R	X	-	X	X	X	X	X	X	-
Scheuer et al. 2003	S	X	X	X	X	X	X	X	-	-
Thormark 2002	R	X	-	X	-	X	X	-	-	-

R residential, *O* office, *S* school, X included, - excluded

2 Description of the low-energy house

The low-energy building under study is an individual family house, which is the main home of four occupants. It is located 80 km south of Turin and built on three levels: two heated floors with a garage underneath. The main geographical and climatic data and some of the most relevant building features are reported in Fig. 1.

The house in Morozzo was designed by *Studio Roatta Architetti Associati* in Mondovì (Italy), in compliance with sustainable and bioclimatic architecture principles, in order to obtain a very low-energy building. The overall goal of obtaining a winter heat requirement ten times lower than the maximum allowed by the thermal regulations in force was reached through exploitation of passive solar contributions, improvement of thermal insulation, enhanced control of air flows (a *blower door test* was performed) and the use of high-efficiency equipment.

The shape of the building, window orientation and the use of static sun screens allowed the winter solar gain to be increased (59% contribution to the gross heat requirement) and the summer overheating kept under control.

The structural system is a reinforced concrete frame partially combined with masonry block walls. The building is insulated with 15-cm cork slabs on the exterior facades, which leads to a thermal transmission coefficient U=0.22 W/m^2 K. The roof is insulated with 22 cm of wood wool (U=0.21 W/m^2 K), and the ground floor is insulated with 10 cm of polystyrene. The total glazed surface consists of 100 m^2 of windows made of low e-coating triple glazing (overall U=1.1 W/m^2 K). Heat is generated by an air-to-water heat pump with a coefficient of performance of 2.54 and an average global seasonal yield $\eta G{,}s$=2.62. Air change is ensured by controlled mechanical ventilation with heat recovery having an efficiency of 75% (T_{ext}=1.7°C−T_{int}=20°C), and the air change rate is assumed to be 0.3 h^{-1}.

With these parameters and considering a thermostat set point of 20°C, the useful heat requirement is 10.38 kW h/m^2. A solar collector supplies about 95% of the yearly energy requirement for domestic hot water (DHW) and 50% of the energy requirement for washing.

3 Methods

LCA literature in the building sector is rapidly growing, as acknowledged in two fairly comprehensive reviews by Sartori and Hestnes (2007) and by Ortiz et al. (2009b).

Among the pioneer papers published between 1998 and 2001, it is worth remarking the important contributions of Blanchard and Reppe (1998), which evaluated the environmental impacts, energy use and life cycle costs of a residential home in Michigan; Thormark (2001), which studied the influence of recycled building materials; Adalberth et al. (2001), which used LCA to compare four multi-family buildings in Sweden; and Peuportier (2001), which compared three types of house with different features in France.

Since then, the literature on building LCA has grown in two directions: LCAs of building materials and components and LCAs of whole buildings. Sartori and Hestnes (2007) reviewed 60 case studies of LCA applied to the whole building, while Ortiz et al. (2009b) reviewed 25 case studies of which 40% dealing with LCA of the whole building and 60% dealing with LCA of building materials and component combinations. Residential buildings are the most represented, but there are also other applications like those reported by Scheuer et al. (2003) who applied LCA to a university building and Kofoworola et al. (2008) who studied a commercial office building in Thailand.

Although the general LCA methodology is well defined, some authors (Sartori and Hestnes 2007; Ortiz et al. 2009b) claim that most existing building LCAs are not comparable to a great extent as they are based upon different approaches and assumptions. For this reason, in order to foster diffusion, acceptance and credibility of LCA in the building sector, assumptions, methodological choices and the results must be presented in a transparent way.

During the last years, beside generic LCA tools (i.e. LCA software applications that are not specific to the building sector), several tools specific to the building sector have been proposed. ATHENA system proposed by Trusty (2000) has classified such tools.

A comprehensive description and comparison of both existing general LCA tools and building-specific tools, which is out of the scope of the present paper, can be found in Zabalza Bribián et al. (2009), Ortiz et al. (2009b), Erlandsson and Borgb (2003), Peuportier and Putzeys (2005), Haapio and Viitaniemi (2008), Lee et al. (2009), Forsberg and von Malmborg (2004) and Ding (2008).

It must be said that both these two kinds of tools are worldwide used, though they both have advantages and drawbacks. Building-specific tools are often preferred because they need less LCA expertise, which usually discourage potential users, they are more user friendly, allow quick and uncomplicated analysis and sometime combine more than one assessment tools (e.g. LCA+LCC). On the other hand, LCA experts usually prefer generic LCA tools, as they are more flexible, allow modelling more complex systems, have access to more extended, updated and transparent databases.

If on one hand building-specific tools are welcome because they encourage adoption of LCA by those who see LCA as too complicated, data intensive, and time consuming, on the other hand, generic LCA tools are welcome too, as they can be more site-specific, more transparent and more precise, for instance, when modelling EOL or evaluating uncertainty.

According to Haapio and Viitaniemi (2008) building-specific tools do not mention if they report the uncertainties, or the margin of error, in the results. Consequently, the user of the tool is not necessarily able to estimate the reliability of the results. Yet, the same authors concluded that comparing the tools and their results is difficult, if not impossible.

Lee et al. (2009) argued that many of the available tools can only be used with significant restrictions because of their differences in design for scope and content and consequently chose to develop their own application. Similarly, other authors developed their own tools (Scheuer et al. 2003; Chen et al. 2001; Mithraratne and Vale 2004; Citherlet and Defaux 2007; Huberman and Pearlmutter 2008; Dewulf et al. 2009; Peuportier 2001; Zabalza Bribián et al. 2009; Kofoworola and Gheewala 2008; Erlandsson and Levin 2005; Gerilla et al. 2007), often retrieving information from several sources.

It must be remarked that according to Ortiz et al. (2009b), Scheuer et al. (2003) and Haapio and Viitaniemi (2008), due to data limitations and due to the large range of construction techniques and material choices, none of the tools are currently capable of modelling an entire building or computing the environmental impacts from all life cycle phases and processes.

Bearing these limitations in mind, as far as the present research is concerned, the reasons in favour of a generic LCA tool prevailed. Among these reasons are the need of handling a complex and detailed systems, with a great number of materials, the availability of updated and transparent inventory datasets, the possibility of modelling a site-specific EOL and evaluating uncertainty. Thus, an ad hoc LCA application was set up using the software SimaPro 7 (PRè Consultants 2006).

3.1 System boundaries

The CEN/TC 350 “Sustainability of Construction works” standard (under development) recommends consideration of four building's life cycle stages: product stage (raw materials supply, transport and manufacturing), construction stage (transport and construction-installation on-site processes), use stage (maintenance, repair and replacement, refurbishment and operational energy use: heating, cooling, ventilation, hot water and lighting and operational water use) and end-of-life stage (deconstruction, transport, recycling/re-use and disposal).

Bearing these recommendations in mind, the system under study was split into the phases and subsystems shown in Table 2. Although the relative contribution of all the stages and subsystems is visible in the flowchart

Geographical and climate data		Building features	
Altitude	**431 m**	Total floor area	367 m^2
Latitude	**44°25' north**	Heated area (H)	192 m^2
Longitude	**7°42' east**	Garage area (G)	174 m^2
Degree Days	**2850**	Reference area (H + $^1/_3$G)	250 m^2
Climatic area	**E**	External wall area (S)	753.9 m^2
Conventional heating period	**183 days**	Shape factor (Surface/Volume)	0.8 m^2/ m^3

Fig. 1 Main features and climatic data of the house in Morozzo

available for downloading as an e-component, it was considered more meaningful to the research to clearly separate the contribution of materials from energy use during the operational phase.

3.2 Functional unit

In LCAs of whole buildings, the functional unit should be defined so that the different buildings being compared provide the same services, for a similar duration. This suggests adoption of 1 m^2/year as functional unit.

According to ISO 14040, "the functional unit is a measure of the function of the studied system". The main function of the house is certainly supplying a human habitation service, which can be directly correlated to the size of the living area (heated). However, the garage is also supplying a service, though of lower quality, and this should also be accounted for when calculating the reference area, which is a measure of the overall service provided. For commercial purposes in Italy, the market value of a house is calculated based on the sum of the living area plus 1/3 of non-heated areas, reflecting the quality of the services provided, and which approach was adopted in the present research (see Fig. 1). The reference area is thus 250 m^2. This means that the model was calculated for the whole building, over 70 years expected occupancy, and the obtained results were divided by 70 and by 250.

However, some readers might think that only the heated area should be considered as a measure of the service provided. They can therefore adapt the value of indicators presented in this paper multiplying by 250 m^2 and dividing by 192 m^2. The change of reference area will not affect the comparison between the low-energy and the standard houses.

3.3 Data collection

Design drawings and bill of material quantities were freely available, and it was possible to enter the worksite at various construction stages; most of the data are therefore site measurements. However, also literature data (see Table 2) had to be used. Datasets for material fabrication, energy chains and transport systems were mostly extracted from the ecoinvent 2 database (ECOINVENT 2007).

3.4 End of life of building materials

The EOL of products is an essential part of every LCA study. However, it should be pointed out that this is probably the most difficult step, as it is necessary to forecast several years in advance a credible (or reasonable) sequence of activities for disassembling and recycling (or disposing) construction and demolition waste (C&DW).

While it is true that disposal of building materials is often disregarded (Althaus et al. 2005) and there is limited quantitative information on the actual demolition process (Scheuer et al. 2003), there are a few studies (Thormark 2002; Blengini 2009; Dewulf et al. 2009) that contain useful quantitative and methodological information on the role of EOL in building sustainability.

Recycling can avoid landfilling and partially displace the environmental impacts of manufacturing, as recycled products can substitute virgin materials, but on the other hand, it is also responsible for impacts related to re-

Table 2 Life cycle phases, subsystems and data sources

Life cycle phase	Subsystem	Source of site-specific data
Pre-use and maintenance	Structure, finishes and equipment material	Quantities estimated from building drawings and field measured data
	Transportation	Average distances from personal communication with designer and contractor
	Construction stage	Field measured data, personal communication with designer and constructor, literature (Blanchard and Reppe 1998; Scheuer et al. 2003; Chen et al. 2001; Citherlet and Defaux 2007; Kellenberger and Althaus 2009)
	Maintenance	Literature (Ortiz et al. 2009a; Scheuer et al. 2003; Chen et al. 2001; Mithraratne and Vale 2004; Citherlet and Defaux 2007; Kellenberger and Althaus 2009; Matasci 2006) and personal communication with designer and constructor
Use	Energy use for heating, ventilating and DHW	Calculated with the software application EDILCLIMA EC501
	Energy use for cooking, washing, lighting and use of appliances	Statistical data (Piano Energetico della Provincia di Torino 1997; MICENE 2004)
End of life	Dismantling, demolition, recycling/re-use/landfill	Literature (Blengini 2009; APAT 2005; Blengini and Garbarino 2006; Brimacombe and Shonfield 2001; Althaus et al. 2005) and unpublished data from Politecnico di Torino on end of life of building materials

processing and transportation. In such a context, it is possible that more energy is spent and more impacts are caused through recycling than energy and impacts saved as a consequence of avoided primary production.

LCA models, like the one here presented, should therefore be extended over the whole recycling chain and should consider credible and reasonable sorting yields, transportation distances, re-processing efficiencies and take into account the quality of the recycled products, in comparison to the correspondent virgin products.

The present research has adopted the *avoided products* approach, according to which the system boundaries are expanded downstream, including all the activities and processes (and their related impacts) from C&DW collection to substitution of virgin products. The environmental burdens corresponding to manufacturing of the substituted product are subtracted from the system. The balance between environmental impacts and gains in the chain (net gain) might therefore be negative, in case the avoided impacts (benefits) are higher than the induced impacts, or vice versa.

The ratio between the net environmental gains of the demolition-recycling chain and the from-cradle-to-gate burdens of embodied materials is called the recycling potential (Blengini 2009). The recycling potential is thus a measure of the environmental impact reduction that can be achieved through an eco-efficient EOL management.

In the opinion of the authors, when based on real processes and fair efficiencies, the avoided product method is the most transparent, and it helps in understanding the benefits and drawbacks of recycling. To improve sustainability, it is not sufficient to state that a material is recyclable (Thormark 2002), or that recyclable materials were used: One also has to consider the forms for recycling, as well as how to provide for disassembly. This said, in order to enhance comparability with other studies, the recycling potential was assessed, but presented separately, with an option for exclusion.

3.5 Data uncertainty

Uncertainty analysis is gaining importance in LCAs, as the existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of the results (Sonnemann et al. 2003). Huijbregts et al. (2003) stressed on the evaluation of parameter uncertainty, scenario uncertainty and model uncertainty.

As a contribution to better understand the reliability of LCAs in the building sector, the LCA presented in this paper was elaborated using data uncertainty estimations and calculating the results not only through a deterministic approach but also in terms of probability distribution using the Monte Carlo method.

As far as the data retrieved from ecoinvent 2 are concerned, these are also available as probability distributions, mostly lognormal, as described in Frischknecht and Jungbluth (2007a).

The definition of the uncertainty of site-specific data was much more complicated, as they were mostly available as single measurements or estimates. Thus, field data uncertainty was evaluated according to the pedigree matrix for uncertainty estimation described in Frischknecht and Jungbluth (2007a), considering the data quality management approach presented in Junnila (2004) and according to an overall data quality judgement by the participants in the research.

Input data were therefore considered as a normal distribution around a deterministic value and a coefficient of variation=standard deviation/mean. The Monte Carlo simulation was run with 10,000 cycles.

3.6 Selection of environmental indicators

The choice of appropriate indicators and commonly accepted methodologies to analyse inventory results is always a subjective step. This was also the case in the present research, where the participants (designers and public administrators) agreed to base the judgement on sound, objective, understandable and internationally recognised indicators. Stakeholder involvement and agreement are in fact essential for acceptance of LCA results (Werner et al. 2007)

Mid-point indicators were chosen to be representative of broadly recognised areas of environmental concern, as well as based on international conventions, agreements and guidelines.

A first group of energy indicators was adopted: cumulative energy demand (CED) relevant to the life cycle primary energy use (Frischknecht and Jungbluth 2007b) and non-renewable energy (NRE), the non-renewable part of CED.

A second group of six environmental indicators included GWP_f (global warming potential with a time horizon of 100 years, excluding the contribution of biogenic carbon dioxide), GWP_b (including the contribution of biogenic carbon dioxide), ODP (ozone depletion potential), AP (acidification potential), EP (eutrophication potential) and POCP (photochemical ozone creation potential). Characterisation factors are reported in IPCC (1996) and Frischknecht and Jungbluth (2007b).

Although CED, NRE and GWP are sometimes regarded as duplications of each other (Kellenberger and Althaus 2009), there were good reasons to consider all of them separately. CED and NRE are remarkably different in low-energy houses like the one here presented, due to the extensive use of wood. In the authors' opinion, non-renewable and renewable energies are both important for mankind, while in some cases, it seems that some people are not concerned about using too much renewable energy, as it is renewable. Low-energy buildings should save energy, regardless of their source, and renewable energies like biomass could reasonably be used for other purposes.

Moreover, although global warming is correlated to energy use, GWP and CED can show different patterns due to decarbonation occurring during clinker burning. This is typical of concrete-framed building, like the one presented here and like the ones discussed in Blengini (2009) and Kofoworola and Gheewala (2008).

As the biogenic carbon cycle in wooden products is often not neutral, as remarked in Peuportier (2001), the influence of the biogenic carbon dioxide balance was also investigated.

Here, it must be said that there are different accounting methodologies to handle carbon uptake during plant growth and biogenic emissions at EOL (Rabl et al. 2007). It is therefore necessary to consistently handle C-uptake throughout the whole life cycle (Werner et al. 2007).

Another important aspect is the use of wooden building materials as carbon sink (Werner and Nebel 2007; Rabl et al. 2007) as stored carbon can be locked up in the biomass for several decades, therefore allowing a steady state level of storage (Buchanan and Bry Levine 1999).

Wooden products in LCA databases like the ecoinvent are usually assigned an ex ante CO_2 credit, which includes the carbon stored in the biomass and the balance between emissions and uptake in the wood production chain (Althaus et al. 2005).

However, when assigning an ex ante credit to wood, one has to make sure that the full life cycle of the biomass is considered, from forestry to EOL (either incineration, landfill or re-use); otherwise, the potential carbon sequestration could be overestimated.

For this reason, a precautionary criterion was adopted to calculate the GWP_b by assigning ex post the CO_2 credit to the re-used wood. Such an approach was perceived by the participants in the research as an incentive to foster re-use of wood. Indeed, it holds analogies with the approach discussed in Rabl et al. (2007) according to which "credit for CO_2 removal should be paid only when and where the wood is replaced by new growth".

4 Life cycle inventory

This section describes the main inventory data of the low-energy house (LEH) in Morozzo. A detailed flowchart of the LCA model is available for downloading as an e-component.

4.1 Pre-use and maintenance

Before starting data collection and modelling, the house was divided into 11 structure and finishes components and four equipment components (see e-component). Inventory tables containing the dataset are reported as an e-component. Construction waste factors, i.e. cutting waste generated during the construction stage, and replacement factors for repair/maintenance of the structure, finishes and equipment were estimated from the literature reported in Table 2, taking into account the designer's and constructor's experience. For what concerns the service duration of

Table 3 Electricity collected from the grid during the use phase

Energy consumption (CV)		
Heating and ventilating	4.7 (10%)	kWh m^{-2} $year^{-1}$
DHW	22.8 (25%)	kWh/year
Cooking	542.5 (25%)	kWh/year
Washing, lighting and use of appliances	1646 (25%)	kWh/year

CV coefficient of variation (standard dev/mean)

building materials, it must be noticed that, as reported by Kellenberger and Althaus (2009), little reliable data on the life span of building components are presently available. Assumptions based on literature were necessary.

4.2 Use phase

The energy consumption during the use phase was separated into uses that depend on the house size (heating and ventilating) and uses that depend on the number of occupants (DHW, cooking, lighting and appliance use).

The winter heat requirement was calculated by the designers according to the architectural and thermo-physical features and the local climate conditions. For that purpose, the designers selected the software application EDILCLIMA EC501 (2006) as they consider it a flexible and reliable tool, which is in compliance with legislative requirements (Decree 192/2005 subsequently amended by legislative decree 311/2006) and the UNI EN 832 standard (UNI 2001). The energy requirement for DHW was calculated considering four occupants with a daily demand of 50 L. Energy used for cooking, washing and lighting was retrieved from the official statistics indicated in Table 2.

Table 3 summarises energy consumption for all the activities in the operational phase. Electricity collected from the grid is the only energy source; therefore, the eco-profile is that relevant to the Italian mix according to the ecoinvent database.

4.3 End of life

Three steps were included in the model for the EOL phase:

1. Selective disassembling of re-usable/recyclable materials and structures (windows, steel, aluminium and roof)
2. Controlled demolition of the structure by hydraulic hammers and shears
3. C&DW treatment and recycling, re-use or landfill

Table 4 summarises the most important parameters describing the EOL model, with emphasis on sorting efficiencies and destination. All the energy consumption and environmental impacts due to transportation, demolition and recycling operations were considered, on the basis of the results of a previous study (Blengini 2009). Inventory data relevant to recycling of aluminium, steel, glass and copper were retrieved from the ecoinvent database, which contains data on both production from scraps (recycling) and from virgin raw materials (avoided products).

The lithoid fraction, i.e. concrete, mortar, bricks, ceramics, etc., was assumed to undergo a recycling process for the production of secondary aggregates. This can be considered a form of open loop recycling as concrete and other high embodied energy building materials are down-graded into recycled aggregates, therefore avoiding the production of natural sand and gravel.

For clarity, it should be mentioned that the C&DW generated from the building process and during maintenance operations was considered to undergo a simplified EOL model, which involved metal and glass separation and recycling, wood incineration and mixed rubble recycling. The EOL of the cutting waste and maintenance materials was included in the “construction stage” and “maintenance” subsystems, respectively, in order to keep them separated from the EOL of the house itself as they occur at different stages.

4.4 Inventory of the standard house (benchmark)

The standard house (SH) mirrors the original in size features, geographical/climatic conditions and service duration of the house in Morozzo. Energy consumption for heating was re-calculated in compliance with the same legislative requirements and the building envelope and equipment were consequently adapted.

The main differences between the SH and the LEH are those relevant to insulation, glazed surface and equipment, as summarised in Table 5. In particular, the window surface was decreased, and consequently, the external walls surface increased. The heat pump was substituted with a natural gas boiler and the solar collector was excluded.

The inventory step was re-elaborated, taking into account the new building features. Heating, DHW and cooking were considered to be powered by natural gas, with no solar contribution (inventory data of the natural gas supply chain from ecoinvent). The energy requirement for lighting and use of appliances remained unchanged. Due to the exclusion of the solar panel, the energy requirement for DHW and washing was increased (see Table 5). The sequence of processes in the EOL remained the same.

Here it should be pointed out that one advantage of the SH, in comparison to the LEH, was the possibility of using gas cooking equipment. Electric cooking equipment had to be selected for the LEH as the use of a standard natural gas device was not compatible with legislative prescriptions due to the insufficient aeration of the kitchen. This penalises the LEH as the from-cradle-to-gate natural gas chain is more efficient than the electric chain.

5 Results and discussion

5.1 Contribution analysis and recycling potential

A contribution analysis is presented in Fig. 2. Structure, finishes and maintenance materials show impacts always higher than the contribution of operational energy during the use phase, except for ODP. The use phase is dominated by "other uses", which have an impact higher than heating, while cooking is remarkably lower, though not negligible. DHW has virtually no relative impact. Equipment, transportation and the construction stage always play a minor role.

What clearly emerged is that, conversely to standard buildings and unlike the findings of other studies (Sartori and Hestnes 2007; Blengini 2009; Ortiz et al. 2009a; Blanchard and Reppe 1998; Scheuer et al. 2003; Adalberth et al. 2001; Junnila 2004; Peuportier 2001), there is not a single subsystem which overshadows the others. Rather, the life cycle impacts are caused by the mutual contribution of several equally (or almost equally) important elements.

Designers and public administrators participating in the study were surprised by the minor contribution of transportation, as it was feared that the triple glazed windows imported from Germany and the cork slab transported from Morocco and Portugal by truck and ship might compromise the environmental performance of the LEH. This result confirms the findings of Peuportier (2001), who estimated the contribution of transportation between 1.5% and 2.4% of CO_2 emissions.

Figure 2 shows the important contribution of the building EOL, which corresponds to a reduction in life cycle impacts between 2% and 17%, depending on the indicator. In terms of recycling potential, i.e. comparing the net environmental saving with the environmental burdens of embodied materials, the LEH showed a potential impact reduction of 32% in terms of CED and 17% in terms of GWP_f.

Therefore, an eco-efficient EOL management can be useful to lower the life cycle impacts. This is an interesting finding that complements previous studies (Huberman and Pearlmutter 2008; Thormark 2002) and might influence the design of future low-energy buildings, as the more operational energy decreases, the more important it is to pay attention to both energy for material production and to the aspects of the recycling potential.

It is also important to notice that the four selected energy and climate change indicators do not duplicate each other. In particular, the contribution of carbon sequestered in the re-used wood remarkably increases the recycling potential and lowers the life cycle greenhouse emissions.

More details on the relative contributions of structure and equipment materials to the primary energy use is supplied as an e-component. The highest relative embodied energy corresponds to wooden products (sawn timber, particle board, wood wool and cork slab). However, it should be remarked that 76% is renewable energy. As far as CED is concerned, concrete comes after wooden products, but is the first contributor to NRE, followed by bricks, steel reinforcing bars and aluminium.

5.2 Scenario analysis: comparison between LEH and SH

The comparison between the life cycle impacts of the LEH and the SH is probably the most meaningful part of the research (Fig. 3). The error bars show the range corresponding to 68% of the results obtained after the Monte Carlo simulation. It must be recalled that, despite the effects of uncertainty on the absolute accuracy of an LCA, comparative LCAs are relatively more accurate, as uncertainty is usually highly correlated between scenarios.

As far as the LEH is concerned, GWP and AP show less disperse results, followed by energy indicators, while ODP, EP and POCP have a higher level of uncertainty. As can be

Table 4 End of life of structure and equipment materials

Material	Dismantling	Demolition	Waste processing
Aluminium	90% R	–	10% R
Glass	90% R	–	10% R
Steel, copper, aluzink	90% R	–	10% R
Steel rebars	–	70% R	30% R
Wooden roof beams	90% RU	10% I	–
Untreated wood	50% RU	50% I	–
Other wooden materials		90% I	10% I
Concrete, brick, ceramic, plaster, mortar, stoneware	–	–	100% R
Others (cork, plastic, gypsum, mineral wool)	–	–	100% L

R recycling, *RU* re-use, *I* incineration, *L* landfill

Table 5 Inventory of the standard house

		Main changes in respect to the low-energy house
Structure and finishes components	Walls	Quantity of bricks increased because of windows reduction (11 t added)
	Roof	OSB panel excluded because of changed type of roof insulation
	Windows	Triple glass windows substituted with double glass
		Total glazed surface decreased (100➔35 m^2)
	Insulation	Cork slab (walls) substituted with polystyrene of decreased thickness (15➔4 cm)
		Polystyrene (floor) thickness reduced (10➔3 cm)
		Wood wool (roof) substituted with polystyrene of decreased thickness (22➔5 cm)
Equipment	Heating equipment	Heat pump substituted with natural gas boiler (condensing)
		Distribution and radiating pipelines increased by a factor 4
	Ventilating equipment	Excluded
	Water equipment	Solar panels excluded
Use phase	Heating	Heat requirement increased from 10.38 to 109.5 kW h m^{-2} $year^{-1}$ (electricity➔natural gas)
	DHW	End-use energy from 22.8 to 2960 kW h/year (electricity➔natural gas)
	Washing	End-use energy from 150 to 300 kW h/year
	Cooking	End-use energy from 542.5 to 774.6 kW h/year (electricity➔natural gas)

observed, there is an increase in the pre-use and maintenance impacts from the SH to the LEH, though it is relatively small. A much more clear difference between SH and LEH is that relevant to the use phase, especially due to heating. As a consequence, while the use phase in the SH is responsible for more than 80% of the life cycle energy use, the contribution of the use phase in the LEH is below 50%. It is also clear that, while the use phase in the SH is dominated by heating, most of the energy consumption in the LEH is related to other uses.

These findings highlight the weight and significance of the pre-use and use phases in low-energy buildings, pointing out that the contribution of material-related energy and environmental burdens cannot be neglected.

A further comparison between the LEH and SH has emphasised some very interesting aspects. The winter heat requirement was drastically reduced from 109 to 10 kW h/m^2, which roughly corresponds to a ratio of 10 to 1 (10:1).

In a from-cradle-to-gate perspective, when considering the overall efficiency of the heat pump/electricity or boiler/natural gas chains, the ratio between the life cycle energy of SH and LEH roughly remains unchanged (9.5:1).

As shown in Fig. 4, when considering the whole use phase, including DHW, cooking, lighting and use of

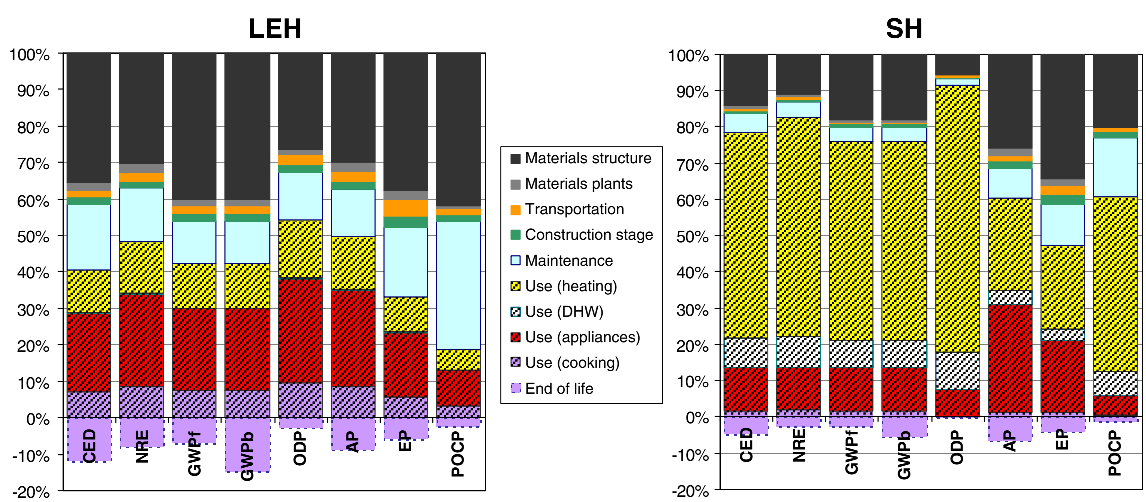

Fig. 2 Contribution analysis of the life cycle subsystems. *LEH* low-energy house, *SH* standard house, *CED* cumulative energy demand, *NRE* non-renewable energy, GWP_f global warming potential fossil, GWP_b global warming potential fossil+biogenic, *ODP* ozone depletion potential, *AP* acidification potential, *EP* eutrophication potential, *POCP* photochemical ozone creation potential

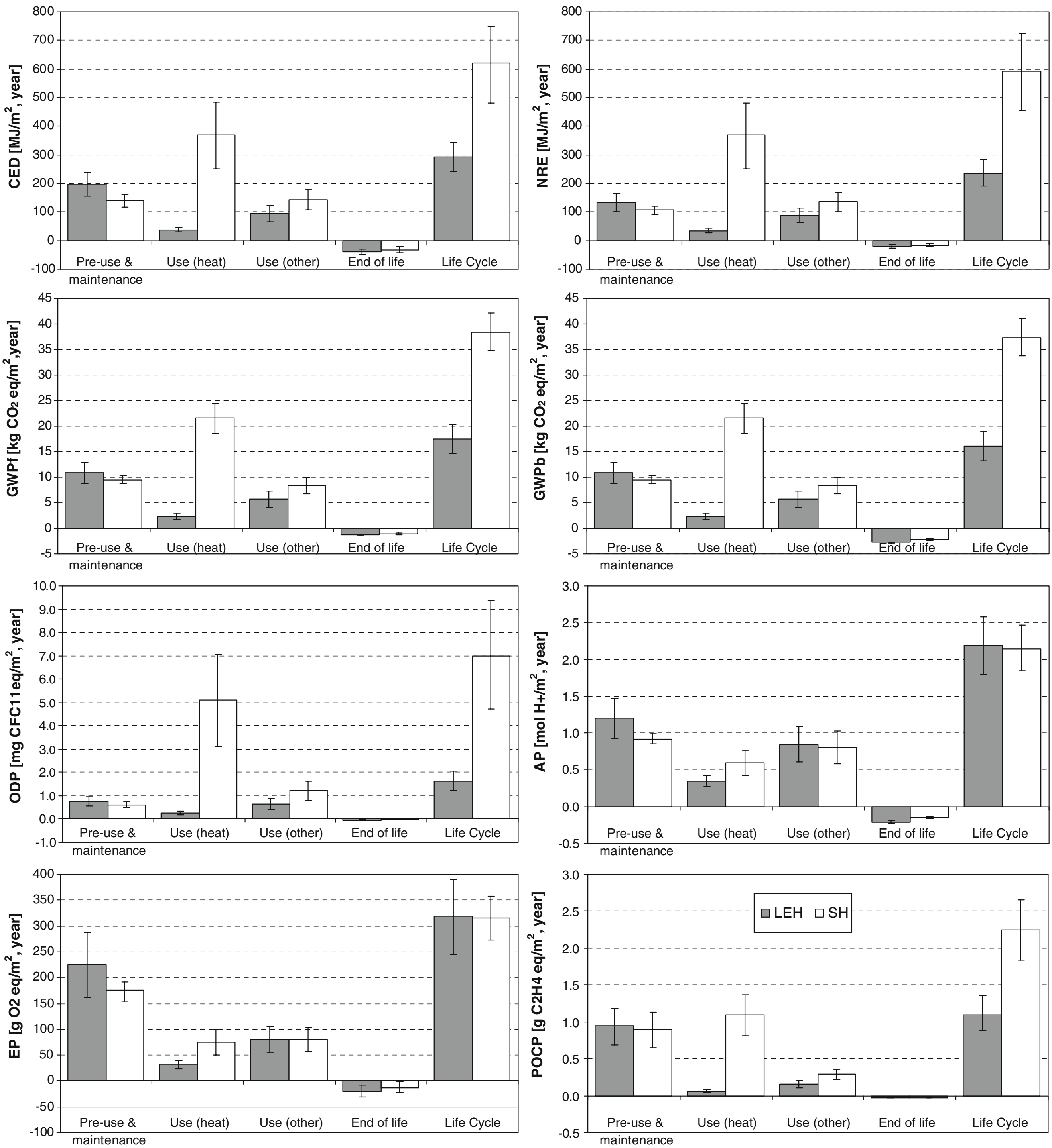

Fig. 3 Comparison between the life cycle phases of the LEH and SH. (*LEH* low-energy house, *SH* standard house)

appliances, the above ratio changes to 3.8:1. Furthermore, when considering the full life cycle, the ratio becomes 2.1:1 in terms of CED and 2.2:1 in terms of GWP_f and 2:1. Surprising is the comparison between LEH and SH in terms of AP and EP: There is almost no difference.

The outstanding energy-saving and environmental performances of the studied LEH were thus confirmed after the life cycle analysis, but to a much lower extent and with the exception of AP and EP. This still remains a very good result, but sensibly reduced in comparison to what was expected by designers and public administrators.

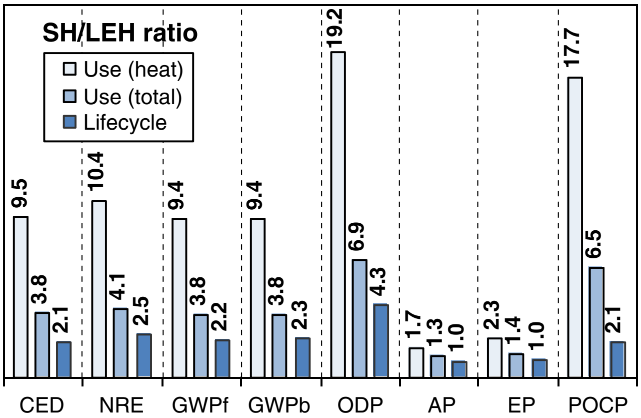

Fig. 4 Environmental gains of the LEH in comparison with the SH (SH/LEH ratio)

5.3 Improvement scenarios

As it was highlighted that pre-use and maintenance represent a very important contribution to the life cycle impacts of the LEH, as well as that cork slabs installed on the exterior facades are responsible of high relative impacts (see also e-component), two alternative thermal-insulating materials were considered. The choice was made taking into consideration insulating materials that are compatible with the building features and the adopted construction technique.

Two materials were considered to represent realistic alternatives: rock wool and expanded polystyrene foam (EPS). In order to provide the same thermal insulation, the thickness was re-calculated, and thus, the 15-cm-thick cork slabs were considered to be equivalent to 15 cm of rock wool (5.4 t) and to 12 cm of EPS (1.07 t). Inventory data were retrieved from the ecoinvent.

It should be said that the use of rock wool in substitution of cork implies operational difficulties during the building stage and additional health hazards for the workers that usually cause extra labour costs of around 30%.

On the contrary, the use of EPS should imply labour cost savings during the building process. However, the acoustic insulation provided by EPS is not sufficient to comply with the legislative prescriptions. This would imply the installation of an additional acoustic insulation system (not considered in the model).

From-cradle-to-gate impacts of pre-use and maintenance related to the three scenarios are reported in Fig. 5. Except for POCP, where the envelope insulated with EPS clearly shows a worse environmental performance, there are no remarkable differences. EPS is preferable when it concerns AP, EP and OD. Rock wool and EPS correspond to a lower CED.

6 Conclusions

A detailed LCA of the house in Morozzo in Northern Italy has highlighted that, when addressing energy-saving and sustainability performances of low-energy buildings, the role and significance of all life cycle phases and subsystems must be carefully considered. Moreover, the lower the operation energy, the more important is the adoption of a life cycle approach.

Over a 70 years' lifetime, the dramatic contribution of material-related impacts has emerged. Structure and finishes materials have the highest relative contribution, but maintenance operations also play a major role. Equipment, construction stage and transportation contributions are minor, though not always negligible.

Unlike standard buildings, where heating overshadows both the rest of the operational energy and the whole life cycle, in the low-energy house, the use phase is dominated by "other uses", i.e. lighting, electric appliances, cooking and DHW.

The role of recycling potential, as an effective tool to decrease life cycle impacts, though postponed in the future, has been estimated from 6% to 35%, depending on the indicator.

It can be said that there is no single dominating item or aspect in the life cycle impacts of very low-energy buildings. Rather, several of them play equally important roles in the overall sustainability. The changing role of life

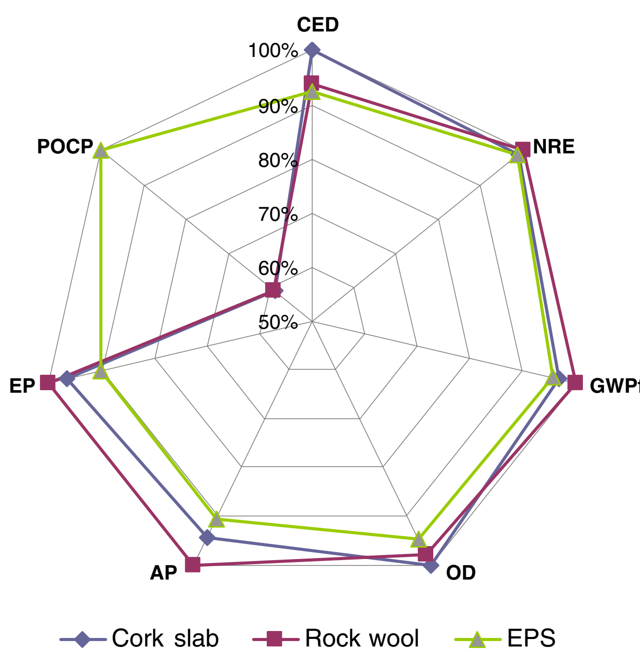

Fig. 5 Improvement scenarios: environmental impacts of pre-use and maintenance according to three types of insulation on the exterior facades

cycle subsystems and their increased inter-dependency fully justify the application of LCA.

As a major conclusion, the overall goal of environmental sustainability behind the construction of the house in Morozzo has been proved to be compatible with the life cycle approach, though applied ex post. The higher embodied burdens were compensated by the remarkable operational energy saving. However, while the winter heat requirement was reduced by a ratio of 10:1, the life cycle energy was only reduced by 2.1:1 and the carbon footprint by 2.2:1.

These results necessarily reflect the complex combination of the case study building unique features, the locally adopted construction techniques, the behavioural pattern of Italian citizens, site-specific climate conditions, local regulations and the Italian energy mix. Bearing this in mind, these results should not be generalised, but some remarks can certainly be given.

Environmental performance of future low-energy buildings should be verified through a holistic approach, as single improvements might not be effective in a life cycle perspective, and could even disappoint expectations.

Detailed LCAs like the one here presented cannot be applied to routine design, but they can support decisions makers, suggesting incorporation of the life cycle approach in energy-saving policies, energy certification and economic incentive schemes, too often lacking in a comprehensive approach that would enhance effectiveness and avoid problem shifting.

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References

Adalberth K, Almgren A, Petersen EH (2001) Life cycle assessment of four multi-family buildings. Int J Low Energy Sustainable Buildings 2:1–21

Althaus HJ, Kellenberger D, Doka G, Künniger T (2005) Manufacturing and disposal of building materials and Inventorying Infrastructure in ecoinvent. Int J LCA 10:35–42

APAT (2005) I rifiuti da costruzione e demolizione. Rome, Italy. http://www.apat.it. Accessed Aug 1, 2009

Arena AP, Rosa C (2003) Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza—Argentina. Build Environ 38:359–368

Blanchard S, Reppe P (1998) LCA of a residential home in Michigan. School of Natural Resources and Environment. University of Michigan, USA

Blengini GA (2009) Life cycle of buildings, demolition and recycling potential: a case study in Turin–Italy. Build Environ 44:319–330

Blengini GA, Garbarino E (2006) Sustainable constructions: ecoprofiles of primary and recycled building materials. Proceedings of the International Symposium Mining Planning and Equipment Selection MPES2006, September 20–22, Turin, Italy.

Brimacombe L, Shonfield P (2001) Sustainability and steel recycling. New steel construction 9(2): 19-21. ISSN 0968-0098

Buchanan AH, Bry Levine S (1999) Wood-based building materials and atmospheric carbon emissions. Environ Sci Policy 2:427–437

Chen TY, Burnett J, Chau CK (2001) Analysis of embodied energy use in the residential building of Hong Kong. Energy 26:323–340

Citherlet S, Defaux T (2007) Energy and environmental comparison of three variants of a family house during its whole life span. Build Environ 42:591–598

Dewulf J, Van der Vorst G, Versele N, Janssens A, Van Langenhove H (2009) Quantification of the impact of the end-of-life scenario on the overall resource consumption for a dwelling house. Resour Conservat Recycl 53:231–236

Ding GKC (2008) Sustainable construction—the role of environmental assessment tools. J Environ Manage 86:451–464

ECOINVENT (2007) Life cycle inventories of production systems. Swiss Centre for Life Cycle Inventories. http://www.ecoinvent.ch. Accessed Aug 1, 2009

EDILCLIMA (2006) Software manual EDILCLIMA. EC501–Edificio Invernale (L. 10/91) vers. 6. http://www.edilclima.it. Accessed Aug 1, 2009

Erlandsson M, Borgb M (2003) Generic LCA—methodology applicable for buildings, constructions and operation services: today practice and development needs. Build Environ 38:919–938

Erlandsson M, Levin P (2005) Environmental assessment of rebuilding and possible performance improvements effect on a national scale. Build Environ 40:1459–1471

Forsberg A, von Malmborg F (2004) Tools for environmental assessment of the built environment. Build Environ 39:223–228

Frischknecht R, Jungbluth N (2007a) Overview and methodology. Data v2.0. Ecoinvent report no.1. http://www.pre.nl/ecoinvent. Accessed Aug 1, 2009

Frischknecht R, Jungbluth N (2007b) Implementation of life cycle impact assessment methods. Data v2.0. ecoinvent report No.3. http://www.pre.nl/ecoinvent. Accessed Aug 1, 2009

Gerilla GP, Teknomo K, Hokao K (2007) An environmental assessment of wood and steel reinforced concrete housing construction. Build Environ 42:2778–2784

Haapio A, Viitaniemi P (2008) A critical review of building environmental assessment tools. Environ Impact Asses 28:469–482

Huberman N, Pearlmutter D (2008) A life-cycle energy analysis of building materials in the Negev desert. Energy Build 40:837–848

Huijbregts MAJ, Gilijamse W, Ragas AMJ, Reijnders L (2003) Evaluating uncertainty in environmental lifecycle assessment. A case study comparing two isolation options for a Dutch one-family dwelling. Environ Sci Technol 37:2600–2608

IPCC (1996) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc.ch/. Accessed Aug 1, 2009

Junnila S (2004) Life cycle assessment of environmentally significant aspects of an office building. Nordic Journal of Surveying and Real Estate Research, Special Series 2

Kellenberger D, Althaus HG (2009) Relevance of simplifications in LCA of building components. Build Environ 44:818–825

Kofoworola EF, Gheewala SH (2008) Environmental life cycle assessment of a commercial office building in Thailand. Int J LCA 13:498–511

Lee K, Tae S, Shin S (2009) Development of a Life Cycle Assessment Program for building (SUSB-LCA) in South Korea. Renew Sust Energ Rev 13:1994–2002

Matasci C (2006) Life cycle assessment of 21 buildings: analysis of the different life phases and highlighting of the main causes of their impact on the environment. Mémoire N. 128/2006. Dissertation, Univ. of Genève

MICENE (2004) Misure dei consumi di energia elettrica in 110 abitazioni italiane. eERG, end-use Efficiency Research Group. Dipartimento di Energetica. Politecnico di Milano.

Mithraratne N, Vale B (2004) Life cycle analysis model for New Zealand houses. Build Environ 39:483–492

Ortiz O, Bonnet C, Bruno JC, Castells F (2009a) Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. Build Environ 44:584–594

Ortiz O, Castells F, Sonnemann G (2009b) Sustainability in the construction industry: a review of recent developments based on LCA. Constr Build Mater 23:28–39

Peuportier B, Putzeys K (2005) Inter-comparison and benchmarking of LCA-based environmental assessment and design tools. http://www.etn-presco.net/generalinfo/index.html. Accessed Aug 1, 2009

Peuportier BLP (2001) Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy Build 33:443–450

PRè Consultants (2006) SimaPro 7 software. http://www.pre.nl/. Accessed Aug 1, 2009

Provincia di Torino (1997) Piano Energetico della Provincia di Torino 1997. http://www.provincia.torino.it. Accessed Aug 1, 2009

Rabl A, Benoist A, Dron D, Peuportier B, Spadaro J, Zoughaib A (2007) How to account for CO2 emissions from biomass in an LCA. Int J LCA 12:281

Sartori I, Hestnes AG (2007) Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy Build 39:249–257

Scheuer C, Keoleian GA, Reppe P (2003) Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy Build 35:1049–1064

Sonnemann GW, Schumacher M, Castells F (2003) Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. J Cleaner Prod 11:279–292

Thormark C (2001) Environmental analysis of a building with reused building materials. Int J Low Energy Sustainable Buildings 2000:1

Thormark C (2002) A low energy building in a life cycle-its embodied energy, energy need for operation and recycling potential. Build Environ 37:429–435

Trusty WB (2000) Introducing assessment tool classification system. Advanced Building Newsletter. http://www.athenasmi.ca/publications/publications.html. Accessed Aug 1, 2009

UNI (2001) UNI EN 832. Thermal performance of buildings. Calculation of energy use for heating. Residential buildings. CEN European Bureau for Standardisation

Werner F, Althaus HJ, Richter K, Scholz RW (2007) Post-consumer waste wood in attributive product LCA. Context specific evaluation of allocation procedures in a functionalistic conception of LCA. Int J LCA 12:160–172

Werner F, Nebel B (2007) Wood & other renewable resources. Int J LCA 12:462–463

Zabalza Bribián I, Aranda Usón A, Scarpellini S (2009) Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 12:2510–2520