The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of a multifamily building in Italy

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Abstract

Purpose Since the construction sector is a considerable energy consumer and greenhouse gas (GHG) producer, the EU rules strive to build nearly zero-energy buildings, by reducing the operative energy and yearning for on-site energy production. This article underlines the necessity to go beyond the energy evaluations and move towards the environmental assessment in a life cycle perspective, by comparing the impacts due to building materials and energy production devices.

Methods We compared the operational energy impacts and those of technologies and materials carrying out a life cycle assessment (LCA; ISO 14040, ISO 14044, EN 15643–2, EN 15978) on a nearly zero-energy building (ZEB), a residential complex with 61 apartments in four buildings, situated near Milan (Italy). We consider all life cycle phases, including production, transport, building site activities, use and maintenance; the materials inventory was filled out collecting data from invoices paid, building site reports, construction drawings and product data sheets. To make the assessment results comparable, we set a functional unit of 1 m^2 of net floor area in 1 year (1 m^2y), upon a lifespan of 100 years. The environmental data were acquired from Ecoinvent 2.2.

Results and discussion The results highlight the important role of the pre-use and maintenance phases in building life so that in a nearly ZEB, the environmental impacts linked to the use are no longer the major proportion: the pre-use phase accounts for 56 %, while the operative energy is only 31 % of the total. For this reason, if the environmental assessment of the case study was shrunk to the operational consumption, only one third of the impacts would be considered. The consumption of non-renewable resources after 100 years are 193,950 GJ (133.5 kWh/m2y); the GHG emissions are 15,300 t (37.8 kg of CO2 eq/m2y). In the pre-use phase, structures have the major impacts (50 %) and the load of system components is unexpectedly high (12 %) due to the ambition of on-site energy production.

Conclusions Paying attention to the operative energy consumption seems to address to only one third of the environmental impacts of buildings: the adoption of LCA as a tool to guide the design choices could help to identify the solution which ensures the lowest overall impact on the whole life, balancing the options of reducing the energy requirements, the on-site production from renewable sources and the limitation of the impacts due to building components (simpler and more durable).

Keywords
Energy and environmental efficiency of residential buildings. LCI data collection for buildings. Life cycle assessment
Production, construction and maintenance impacts of buildings. System-related impacts. Zero-energy buildings (ZEBs)

1 Purpose

One of the main environmental goals of the European Union is to reduce the environmental impacts of the construction sector. The member states have been working for several years to decrease the operative energy requirements to near zero. The aim of this research is to widen the perspective, consider the life cycle point of view and to set side by side some other

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indicators in addition to the energy consumption. Adopting the life cycle assessment (LCA) could be useful to compare the environmental impacts due to the materials and systems production and the building construction and its maintenance with the expected environmental burdens related to the energy consumptions during the use phase. Therefore, to verify the balance among the impacts connected to the operational energy and the impacts due to technologies and materials, we chose a nearly zero-energy building as a case study and we carried out an environmental analysis with the life cycle assessment method, according to ISO 14040:2006 (ISO 2006a), ISO 14044:2006 (ISO 2006b), EN 15643–2:2011 (EN 2011a) and EN 15978:2011 (EN 2011b).

The purpose of this research can be summarized in four key points chosen for their relevance to the aim of this study. Firstly, we recognize the necessity to go beyond the energy evaluations and to move towards the environmental assessment, expanding the set of indicators with the aim of comparing the energy profile with the effects on a list of other environmental subjects. Secondly, we expanded the time span on the whole life cycle to verify the relationship between the more focused operative stage and the phases of production, transport, construction, maintenance and disposal of the building materials and components. As a matter of fact, indeed, the majority of the LCA analysis assesses the construction and maintenance activities through corrective factors in percentage instead of real data. Thirdly, we would like to compare the production impacts due to the building materials intended in a literal meaning (concrete, bricks, steel, wood, insulation) and the production impacts linked to the devices for energy production (heating, ventilation and air conditioning (HVAC), PV system, domestic hot water production, geothermal heat exchanger) and for the building climate behaviour control because in the last decade, it has been observed the gradual growth in the number of the installed devices. Finally, we paid special attention to the data collecting about the characteristics of building materials, transport and building site activities to carefully assess these phases, overcoming the differences among design documents, construction documents and buildings. In this study, we intended the embodied energy as the sum of all the primary energy used to manufacture products and the operational energy as the sum of all the primary energy used in buildings during their operational phase, such as heating, cooling, ventilation and hot water production.

2 Introduction

The Kyoto Protocol (United Nations 1997), enclosed in the United Nations Framework Convention on Climate Change (UNFCCC), was signed by 180 countries in 1997 and came into force in 2005. The main goal was to reduce the emission of greenhouse gasses (GHGs) by at least 5 %, below 1990 levels, in the time span 2008–2012. Moving beyond this purpose, the European Union countries set new targets in 2007, with the aim to become highly energy efficient and low carbon economies by the year 2020. Current new goals are the reduction of the consumption of primary energy derived from fossil fuels by 20 %, in order to reduce greenhouse gas emissions by at least 20 %, as well as to improve the use of renewable energy by 20 % (European Commission 2009). In addition, the European Union has been working for more than 15 years to improve the energy efficiency in the building sector. As a matter of fact, buildings represent about 35 % of the total final energy consumption in the OECD countries, but if we also consider the primary energy consumptions, this ratio comes up to about 40 % (IEA 2008). More in detail, in the year 2010, building is the largest energy end-use sector in EU countries (42 %) (Lapillonne et al. 2012), followed by transport (32 %), industry (24 %) and agriculture (2 %). It is also crucial to underline that the energy consumptions of the building sector have increased by around 1 % every year from 1990 to 2010 (Lapillonne et al. 2012), starting from 37 % of the total consumptions in 1990, and more than two thirds of the total energy consumption is linked to the residential buildings.

For these reasons, the European Parliament and the European Council pushed towards a better energy efficiency in the building sector through the emanation of the Directive no. 2002/91/CE (European Parliament 2002), enacted on 16 December 2002 and entitled “On the energy performance of buildings”. Its purpose was “to promote the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness”. This law was repealed by the Directive no. 2010/31/EU (European Parliament 2010), enacted on 19 May 2010 and titled as before. The general purpose of these laws is to reduce as much as possible the operative energy consumption of buildings, especially the heating requirements, in order to pursue the sustainability goals set by the European Union.

Before, and in parallel to, the Directive, in the later years of the 1900s and in the first decade of the 2000s, a wide array of measures has been adopted by the member states and by independent organizations to actively promote a better level of energy performance of buildings. Among these, we can mention the national energy and sustainability certification systems and the Passive House concept by the “Passivhaus Institut”. Finally, in order to dramatically improve the energy efficiency of buildings, the Directive no. 2010/31/EU (European Parliament 2010) laid down that all new buildings must be “nearly zero-energy buildings (nZEB)” by 31 December 2020, reducing this timeframe by 2 years for buildings owned or used by public bodies. Even if a clear and commonly accepted definition does not exist, the wording nearly zero-energy building usually means a building which has a very high energy performance, and the low amount of energy required for operation should be covered by energy from renewable, non-polluting and low-cost sources. Moreover, since the energy supply should be limited, the directive stimulates the on-site or near-site energy production, to promote the energetic self-sufficiency in the construction sector. The definition of nearly zero-energy buildings, through a numerical threshold for primary energy in use expressed in kWh/m^2 per year, is under jurisdiction of each country.

The established goals cause first and foremost the need for the member states to work on the definition of the energy performance requirements for buildings, in connection with every specific climatic condition of their geographic areas. All of the countries have to define these issues without any interference with the other functional aspects of buildings that are already encoded by standards, such as the intended use, safety or accessibility for people with disabilities. Therefore, the new energy requirements will likely affect the thermal characteristics of the building envelope, the efficiency of heating, cooling and mechanical ventilation systems and the energy supply. The new levels of performance have to be technically, functionally and economically feasible. Particularly, the directive introduces the concept of "cost-optimal level", that means to determine the level of the energy performance that involves the lowest cost application during the expected economic life cycle. The economic compatibility of the new minimum requirements is emphasized in many articles of the directive, in order to establish a new strong link between the energy behaviour of buildings and the economic profile of activities in the built environment.

The directive contemplates a life cycle approach with regard to the economic aspect but avoids any verification about the environmental impacts generated by building construction, maintenance and disposal. As a consequence, all the national regulations and the independent initiatives work on the reduction of the energy requirements during the operational phase, resulting in a tangible reduction of energy costs, without any consideration on the environmental impacts linked to all the other life stages, from production of building components to final disposal, through maintenance and refurbishment. In this context, we are able to underline two different approaches to the energy efficiency of the buildings. In the eldest initiatives, the main goal was to reduce the energy requirements mainly due to winter heating: the most efficient solution was to improve the thermal performance of the building envelope. For this reason, many regulation systems set the limits for thermal transmittance and for heating requirements for each square metre of net floor area. For example, we can cite the *U*-value limit for external walls, roofs and windows in the local rules for energy efficiency, or the "specific space heating demand" in a residential Passive House (kWh/m^{2}y) (Passive House Institute 2013). On the contrary, the Directive no. 2010/31/EU (European Parliament 2010) sets a different approach because of a lack of numerical definition of "zero-energy concept": to achieve a zero-energy level, it is possible to greatly implement the energy production from renewable resources or to improve the systems efficiency rather than pursuing a strong reduction in the energy needs. In this case, the balance between the two actions is closely dependent on the economic issue, sometimes considered in a life cycle perspective, rather than on the environmental matter.

Even if the future scenario set by the European Directive (European Parliament 2010) sees a trend towards the development of zero-energy buildings and according to IEA (2013) the ZEB target should be reached no later than 2030, a comprehensive and commonly adopted definition of them is far from to be achieved, both within the scientific community and in the European and national rules. Over the last 9 years, several interpretations have been proposed and each of them requires different ways of designing this type of building and different ways of relating them with the environmental context. Torcellini et al. (2006) provided some interpretation of "zero concept", Torcellini and Pless (2010) and Marszal et al. (2011) classified the supply options with regards to the positioning of the energy generation; Sartori et al. (2012) and Hernandez and Kenny (2010) suggested two methods to calculate the energy balance. The last two authors introduced in the zero balance also the quantification of the embodied energy in building materials and components, in addition to the in-use energy consumptions; even though, the current standards do not contain any reference to this point of view. Also, IEA (2013) reported the existence of multiple definitions but focuses attention on three key elements: requirement reduction, energy production from renewable sources or green power purchase and cost control. Regarding the latter, according to IEA (2008), the reference scenario should be at least 30 years for cost recovery. Finally, the current rules do not pay specific attention to the preservation of the efficiency level achieved at the end of the construction process, over all the useful life of the building.

The Swiss energy certification system, named MINERGIE®, since 2010, adopted an environmental strategy intended to control the sustainability level of building materials together with the reduction of the operative energy requirements (Association MINERGIE® 2011). The more advanced type of certification, called MINERGIE-A®, prescribes a maximum content of grey energy of 50 kWh/m^{2}y, in addition to the general requirements on the operational energy saving (thermal insulation of the envelope, heating demand reduction, renewable resources, mechanical ventilation system). The grey energy of the building includes the life cycle energy of the envelope and structural materials and the system components (solar and PV panels, heating, ventilation, sanitary). The IEA EBC Annex 57 (2015) is working in the same direction: this working group collected and analysed many research results concerning the embodied energy and the carbon dioxide emissions related to the building sector. The aim is to develop guidelines to assess these two environmental aspects in buildings and to define new design strategies for buildings with less embodied energy and less carbon emission.

In spite of this condition, the EU regulations set as a main goal the reduction, as much as possible, of energy requirements through design choices and, afterwards, the energy production from renewable resources. However, many designers take care to install a large number of devices for energy production and for consumption control, rather than to reduce the energy requirements. In addition, since the assumptions about the energy balance calculation are not well specified or commonly accepted, the electrical needs for the users' activities are generally excluded from the energy balance. With this premise, the nearly zero balance could be reached by increasing the devices for energy production rather than with a better efficiency of the building.

3 Life cycle assessment of zero-energy buildings

In the literature, we can identify a few studies that take into account the relationship between the consumed energy during use and the embodied energy (Sartori and Hestnes 2007; Verbeeck and Hens 2010; Berggren et al. 2013) in low- and zero-energy buildings; in some other studies (Blengini and Di Carlo 2010; Citherlet and Defaux 2007; Blom et al. 2011; Peuportier et al. 2013), the evaluation affects the environmental profile and not just the energy consumptions. Sartori and Hestnes (2007) conducted a comparative analysis of 60 case studies evaluated in a life cycle perspective. They verified that, although the buildings have different characteristics (technologies, materials, size, lifespan) and are located in different countries, there is a common aspect: the reduction of the operating energy needs in low-energy buildings is achieved by improving the performance of the building envelope and the technical systems. For this reason, the embodied energy in low-energy houses is greater than in conventional buildings, in some cases rising up to 46 % of total energy consumptions (embodied energy + operative energy). Blengini and Di Carlo (2010) assessed the environmental profile of a low-energy house, comparing it with the same unit with conventional characteristics. Even in this case, the goal of reducing the operational energy consumption involves a consistent increase of the environmental impacts due to the production of building components and, to a lesser, but not negligible extent, to maintenance activities. As a consequence, even if the ratio between the winter heat requirement of the standard house and of the low-energy one is 10:1, the ratio of energy consumptions and greenhouse gas emissions over 70 years is only 2:1. Citherlet and Defaux (2007) compared three variants of the same house, and they verified that the strong reduction of the final energy (from standard level to Minergie level and to low-energy level) significantly modify the ratio between the environmental impacts linked to the use phase and the other phases. The non-renewable energy consumption of construction and maintenance are about 20 % of the total in the standard house and 50 % in the low-energy one; the global warming potential (GWP) ratio moves from 25 to 80 %. Verbeeck and Hens (2010) affirm that in low-energy buildings, the embodied energy is higher than the operational energy but the total consumptions are lower than in the standard buildings. In the review study of Berggren et al. (2013), it is stated that the embodied energy generally increases when the operational energy decrease but this is not true as far as the step from low-energy building to Net-ZEB is concerned, if the systems for energy production from renewable resources are properly designed and are able to completely cover the operating energy needs. In Minergie-A buildings—MINERGIE® is the Swiss energy certification system—(Associazione MINERGIE® 2014), if the operating energy and the inhabitants' energy consumptions are included, the embodied energy is about 35 %. Of the embodied energy, 60 % is due to building elements and 40 % to thermal plants and solar systems. Blom et al. (2011) found that in low-energy buildings, due to the reduction of gas demand for heating, the production of domestic hot water and the electricity consumptions of household' appliances are more impacting. In spite of the increasing efficiency of the latter, the energy consumptions related to inhabitants keep on growing because of the increasing number of devices per user. Peuportier et al. (2013) confirm the strong influence of household behaviours on the environmental profile of residential buildings. Even if the environmental ranking between standard and passive houses is always in favour of the latter, the transition between economic and expensive use affects more on the passive building. Some researches are focused on the energy aspects (Wang et al. 2009; Ferrante and Cascella 2011; Lund et al. 2011) while other authors present studies on the environmental profile of low- and zero-energy buildings taking into account additional parameters, such as exergy (Yang et al. 2008), emergy (Srinivasan et al. 2012) and costs (Marszal et al. 2012; Leckner and Zmeureanu 2011). All the studies point out that, although the overall consumed energy on a useful life scenario of 50 years or more is less in low-energy buildings than in conventional ones, the balance between the operative consumptions and those concerning the other phases changes substantially and the materials production intensifies its relevance. In this context, it should be noted that many factors are set differently in the studies, making comparisons difficult: data capture about materials and consumption, evaluation of transport, construction and maintenance phases, integration of household consumption and useful life scenarios. As a consequence, to better identify the actual advantages of low-energy buildings, it could be convenient focusing on the system boundaries (in order to avoid the exclusion of components that may generate not negligible impacts), on the impacts not conditioned from the building use and on the energy consumptions rather than heating.

4 Data collection in life cycle assessment studies of buildings

Over the past 15 years, the LCA has been shown to be an appreciable method to verify the sustainability level of buildings and the number of published LCA analysis has grown constantly. The most relevant difference between buildings and industrial products is linked to the uniqueness of every building, even if the same materials and components have been used in many of them. For this reason, some key points about the LCA of buildings are the sources of quantitative data, the moment in which the information is acquired (pre-construction or post-construction) and the life cycle phases considered (only use; production and use; all the stages including transport, construction and maintenance). A general overview on the scientific literature concerning the LCA of whole buildings was conducted with the purpose to understand which life cycle phases were included in those studies, which were the sources of the inventory data, which were the environmental indicators analysed and which were the lifespan scenarios chosen. The declared functional unit and information about the system boundaries and the cut-off rules were also detected. The final results of this overview highlight some different approaches that are presented in the following Table 1. With regards to the life cycle phases and the characteristic of the data collection process, we consider six different situations:

- Measurement: if the data were acquired through on-site direct measurements (Meas);
- Manufacturers: if the data were acquired through interviews to manufacturers, builders or contractors (Manuf);
- Design: if the data were acquired through the design documents (Design);
- Hypothesized: if the impacts were hypothesized without on-site direct measurements (Hp);
- Literature: if the impacts were included with reference to data acquired from the literature (Lit).

We found that the construction phase is the most excluded or, at most, included with reference to the literature data. The reason for this can be explained by the great difficulties that the researchers met in the collection of primary data directly on-site because the LCA analysis are generally conducted after the end of the construction process and the contractors can rarely provide information about the consumptions of the building site activities. The end of life stage is excluded in many cases or can be included on the basis of literature data; in our opinion, the impacts caused by the last life cycle phase are affected by the uncertainty of the assumptions and the wide temporal distance. However, the phases of transport, construction, maintenance and disposal are frequently included on the basis of hypothesized data or information taken from a few literature references cited several times. It is important to underline that the construction sector is strongly influenced by climatic, environmental, technological and cultural conditions of the geographic area in which the building is located, so the literature information can be useful and adaptable only in some specific case studies.

As reported in Table 1, we highlight two recent studies in which the data were acquired through on-site direct measurements or by interviews of manufacturers, builders and contractors in each phase (Blengini and Di Carlo 2010; Radhi and Sharples 2013). In two more cases, the on-site data collection was limited to the production stage (Cuéllar-Franca and Azapagic 2012; Iyer-Raniga and Chew Wong 2012), while the data collection through the interviews of the operators are more frequent (Adalberth et al. 2001; Citherlet and Defaux 2007; Gustavsson and Joelsson 2010; Gustavsson et al. 2010; Kofoworola and Gheewala 2009; Ortiz et al. 2009; Scheuer et al. 2003). With regards to the use phase, almost all research considers both the energy requirements due to the system operations (as heating, cooling, mechanical ventilation and domestic hot water production) and the energy consumptions linked to the users activities (as lighting, cooking). We point out that the latter typology of consumptions is influenced by the inhabitants' behaviours, and for this reason, it has to be excluded from the analysis or has to be reported separately according to the EN 15978:2011 (EN 2011b). With regard to maintenance activities, only three authors (Blengini and Di Carlo 2010; Junnila 2004; Radhi and Sharples 2013) collected information from measurements or from interviews to manufacturers, while in the majority of cases, the data are hypothesized. For example, in one case (Blengini and Di Carlo 2010), the system elements are replaced after 35 years while all the other components are considered to have only minor repairs; in three studies (Cuéllar-Franca and Azapagic 2012; Ortiz et al. 2009; Radhi and Sharples 2013), the windows are replaced after 25 years and in another one (Peuportier et al. 2013) after 30, but this scenario does not match the Italian practice where the windows usually last 50 years, according to manufacturers. The building lifespan scenarios are different and vary from 35 years (Erlandsson and Levin 2005; Gerilla et al. 2007) to 100 years (Gustavsson et al. 2010;

Table 1 Overview of the literature on life cycle assessment of whole buildings

Author	Year	Country	Type of building	FU	Indicators	Useful life	Materials data	Transport	Construction	Maintenance	Use	End of life
Adalberth et al.	2001	Sweden	Apartment building	Net floor area	GWP, AP, EP, POCP, HTP	50	Manuf, Design	Hp	Lit	Hp	Hear, DHW, MV	Hp, Lit
Arena, De Rosa	2003	Argentina	School building	Technology	NRE, GWP, AP, EP, POCP, HTP	50	Design	–	–	–	Heat	–
Asif et al.	2007	UK	Semidetached house		EE, CO_2, SO_X, NO_X	–	Design	–	–	–	–	–
Blengini	2009	Italy	Apartment building	Net floor area	GER, GWP, ODP, AP, EP, POCP	40	Design	Hp	Meas	Hp	Heat, Cool, DHW, El	Meas
Blengini, Di Carlo	2010	Italy	LE detached house	Net floor area	GER, NER, GWP, ODP, AP, EP, POCP	70	Meas, Design	Meas,	Meas, Manuf, Lit	Manuf, Lit	Heat, DHW, MV, El	Lit
Blom et al.	2011	Netherlands	Apartment building	Whole build.	En, ADP, GWP, ODP, POCP, HTP, FAETP, TETP, AP, EP	1	–	–	–	–	Heat, DHW, MV, El	–
Chen et al.	2001	Hong Kong	Apartment building	Net floor area	En	40	Design	Hp	Hp, Lit	Hp, Lit	Heat, MV, El	Hp
Citherlet, Defaux	2007	Switzerland	Detached house	Net floor area	NRE, GWP, AP, POCP	–	Manuf	Hp	–	Hp, Lit	Heat, DHW, MV, El	Hp, Lit
Cuéllar, Azapagic	2012	UK	Detached, semidetached, terraced houses	Net floor area	GWP, AP, ADP, EP, ODP, HTP, TETP, FAETP, MAETP, POCP	50	Meas, Manuf, Lit	Hp	Lit	Hp	Heat, Cool, DHW, El	Lit
Erlandsson, Levin	2005	Sweden	Apartment building	Whole build.	GWP, AP, EP, POCP, Biodiversity	35	Hp	Lit	–	Hp	Heat, DHW, MV, El	Lit
Gerilla et al.	2007	Japan	Detached house	Resid. unit	GWP, AP, EP, POCP	35	Hp	Hp	Hp	Hp	Heat, DHW, El	Hp
Gustavsson et al.	2010	Sweden	Det, terr, apt building	Net floor area	En, CO_2	50	Lit	Lit	–	–	Heat, DHW, MV, El	Lit
Gustavsson et al.	2010	Sweden	Apartment building	Net floor area	En, CO_2	50–100	Manuf, Design	–	Lit	Hp	Heat, DHW, MV, El	Lit
Huberman and Pearlmutter	2008	Israel	House	Resid. unit	En, CO_2	50	Design	Hp	Hp	–	Heat, Cool, DHW, MV, El	Lit
Iyer-R., Chew W.	2012	Australia	Heritage buildings	Net floor area	En, GWP, POCP, EP, Land use, Water	100	Meas	Hp	Lit	Lit	Heat, Cool	Hp
Junnila	2004	Finland	Office building	Whole build.	GWP, AP, EP, POCP, Heavy metals	50	Design	Lit	Hp	Design	Heat, Cool, MV, El	Hp
Kellenberger and Althaus	2009	Switzerland	Virtual detached house	Envelope a.	NRE, RE, EI 99	80	Hp	Hp, Lit	Hp, Lit	Hp	Heat, DHW, El	Hp
Kofoworola and Gheewala	2009	Thailand	Office building	Gross floor a.	En	50	Manuf, Design	Manuf, Lit	Manuf	Hp	Cool, DHW, MV, El	Hp
Matasci	2006	Switzerland	Detached house	Resid. unit	NRE, EI 99, URB 97	80	Design	Hp, Lit	–	Hp	Heat, El	Hp
Mithraratne and Vale	2004	New Zealand	Virtual detached house	Whole build.	En	100	Hp, Lit	Hp, Lit	Hp, Lit	Hp, Lit	Heat, DHW, El	–
Ortiz et al.	2010	Spain	Detached, semidetach	Net floor area	GWP, AP, ODP, Ionising radiation	50	Design	Hp	Hp	Hp	Heat, Cool, DHW, MV, El	Hp

Table 1 (continued)

Author	Year	Country	Type of building	FU	Indicators	Useful life	Materials data	Transport	Construction	Maintenance	Use	End of life
Ortiz et al.	2009	Spain	Detached house	Net floor area	GWP, AP, ADP, ODP, HTP, TETP	50	Manuf, Design	Hp	–	Hp	Heat, Cool, DHW, MV, El	–
Peuportier et al.	2013	France	Passive attached h.	Net floor area	En, GWP, AP, EP, Biodiversity, HH, Odour, Resource, Smog, Waste, Water	50	Design	Hp	Hp	Hp	Heat, DHW, MV, El	Hp
Peuportier	2001	France	Detached houses	Net floor area	En, GWP, AP, EP, ODP, POCP, ADP, HTP, FAETP, Odour, Waste, Water	80	Hp	Hp	Lit	Hp	Heat, Cool, DHW, MV, El	Hp
Pons, Wadel	2011	Spain	Virtual standard school	Room	Materials weight, En, CO_2, Human and Env. toxicity, Materials intensity, Water, Waste, Recycled and Recyclable m.	50	Hp	Hp	Hp	Hp	Heat, Cool, DHW, El	Hp
Radhi, Sharples	2013	Bahrain	Traditional house	Heat gain	CO_2, En, Operative En	60	Meas, Manuf, Lit	Meas, Manuf, Lit	Meas, Manuf, Lit	Meas, Manuf, Lit	Heat, Cool, MV, El	Lit
Sartori, Hestnes	2007	Several	60 buildings	Net floor area	En	30 to 80	Several results	Several results	Several results	Several results	Several results	Several r.
Scheuer et al.	2003	USA	Office-hotel building	Whole build.	NRE, GWP, ODP, EP, AP, Waste	75	Manuf, Design	Hp	Lit	Hp	Heat, Cool, DHW, MV, El	Hp
Sodagar et al.	2011	UK	Semidetached house	Net floor area	CO_2	60	Design	–	–	–	Heat, DHW, MV, El	–
Tae et al.	2011	South Korea	90 flats, 5 typologies	Net floor area	CO_2	60	Hp	Hp	Hp	Hp	Heat, El	Hp
Thormark	2002	Sweden	Terraced houses	Net floor area	En	50	Design	Hp	–	Hp, Lit	Heat, DHW, MV, El	Hp
Yu et al.	2011	China	Prototype house	Resid. unit	En, CO_2	–	Lit	Hp	Lit	–	–	Hp

GER gross energy requirement, *NRE* non-renewable energy, *GWP* global warming potential, *AP* acidification potential, *ADP* abiotic depletion potential, *EP* eutrophication potential, *ODP* ozone layer depletion potential, *HTP* human toxicity potential, *TETP* terrestrial ecotoxicity potential, *FAETP* freshwater aquatic ecotoxicity potential, *MAETP* marine aquatic ecotoxicity potential, *POCP* photochemical ozone creation potential, *Design* data acquired by design documents, *Hp* data hypothesized without direct measurement, *Lit* data acquired from literature, *Manuf* data acquired from manufacturers, builders and contractors, *Meas* data acquired by direct measurement, *Cool* summer cooling, *DHW* domestic hot water, *El* electricity, *Heat* winter heating, *MV* mechanical ventilation

Iyer-Raniga and Chew Wong 2012; Mithraratne and Vale 2004), but almost half of the articles reported 50 years as the expected building life.

The methods and the sets of the environmental indicators chosen are very different among the research and almost half of them consider only the energy consumptions or the emissions of CO_2 (see Table 1). Many evaluations are based on the main indicators recommended by EN 15978:2011 (EN 2011b), such as global warming potential, ozone layer depletion potential, acidification potential, eutrophication potential, photochemical oxidation potential and abiotic resources depletion potential. Every one of these parameters are not always considered, and in some cases, they are supported by other indicators, such as human toxicity potential, water use or waste production (see Table 1).

In the most part of the analysed research, the LCA results are expressed in relation to 1 m^2 of net floor area in 1 year (1 m^2y) which seems to be the most clear and useful functional unit to describe the environmental profile of buildings and to allow the comparison among similar but not equal objects. In some cases, the functional unit is set as the whole residential unit or the whole building with explicit data about the net floor area or the heating area (Huberman and Pearlmutter 2008; Junnila 2004; Mithraratne and Vale 2004; Scheuer et al. 2003). On the contrary, in two studies, the functional unit is declared to be strictly linked to the characteristics of the building and the object of the research with, unfortunately, no interest for the comparison of the outcomes with other studies. Arena and De Rosa (2003) define the functional unit as "the environmental impact of the implementation of a given technology in the school building", since the scope of their LCA analysis is to compare different building technologies to be applied in a school to improve the thermal comfort. Radhi and Sharples (2013) select the "external heat gain" as the functional unit because their study concerns only the facade layers and the electricity consumed by the HVAC system.

Besides the definition of the scope and the functional unit, the description of the system boundaries is as fundamental. In the most recent analysed studies, we can note that the authors usually report in an explicit way the phases and the building components included or excluded in the assessment, and the boundaries of the system are simpler to understand (Blengini 2009; Blengini and Di Carlo 2010; Cuéllar-Franca and Azapagic 2012; Gustavsson and Joelsson 2010; Iyer-Raniga and Chew Wong 2012; Ortiz et al. 2009, 2010). On the contrary, in the older studies, the system boundaries are often not declared. Especially in older studies, the cut-off rules are not clearly expressed and it is often difficult to understand which building components are really included in the assessment and which are omitted; the reports are particularly unclear about the systems and finishes materials. In the same way, the cut-off rules concerning the phases of transport, construction and maintenance are not easily detectable.

In conclusion, we state that through this overview, we recognized a general variability in the scope of the studies, in the analysed aspects, in the data acquisition and quality, in the assessed indicators of impacts and, sometimes, also in the functional unit; moreover, in some articles, the system boundaries, the data sources, the analysed life cycle phases and the expected service life are not clearly illustrated. This condition was also underlined by other review authors, and the main result consists of the fact that it is almost impossible to make a comparison among the outcomes of the assessments (Sartori and Hestnes 2007; Khasreen et al. 2009; Optis and Wild 2010).

5 The case study: residential buildings in Milan

The life cycle assessment described in this paper has the aim of highlighting the relationship between the environmental impacts due to the energy consumption during the operational phase and the environmental impacts related to the construction, maintenance and disposal activities. Besides, the environmental burdens of materials, divided by categories, will be considered. The case study evaluated is a residential complex recently built in a small town in the hinterland of Milan, in Northern Italy. As shown in Figs. 1 and 2, it is composed of four buildings with linear typology arranged around a wide courtyard (see Figs. 3 and 4) and placed upon an underground basement. They are two-storey buildings plus a mansard floor upon the ground; they are subdivided into 61 apartments of different typologies, grouped in 12 blocks with a stairwell in each. The total net floor area is about 4000 m^2, and the floor area of the residential ancillary spaces (unheated attics, stairs and technical rooms) amounted to about 2100 m^2. The buildings are built on a large underground basement which includes 90 garages, with a floor area of 3300 m^2 and some technical rooms, ancillary spaces and an inaccessible compartment that fill an additional 3700 m^2. We highlight that the extension of the foundation slab has not been determined by structural or architectural reasons but by the energy needs: the extension of the geothermal heat exchanger, and that of the foundation slab which contains it, has been sized as a consequence of the heat demand. As a result, it was built an underground floor area greater than what allowed by the planning rules and larger than the actual necessity (about 1800 m^2 more) (Table 2).

We chose this residential complex as an example of a type of building which can be considered in compliance with the Directive no. 2010/31/EU (European Parliament 2010), even if it was planned some years before. This is because traditional typologies, materials and construction techniques, chosen for coherency reasons with the surrounding context, were joined with targets of high energy efficiency and devices for the on-site energy production in order to build a complex classifiable

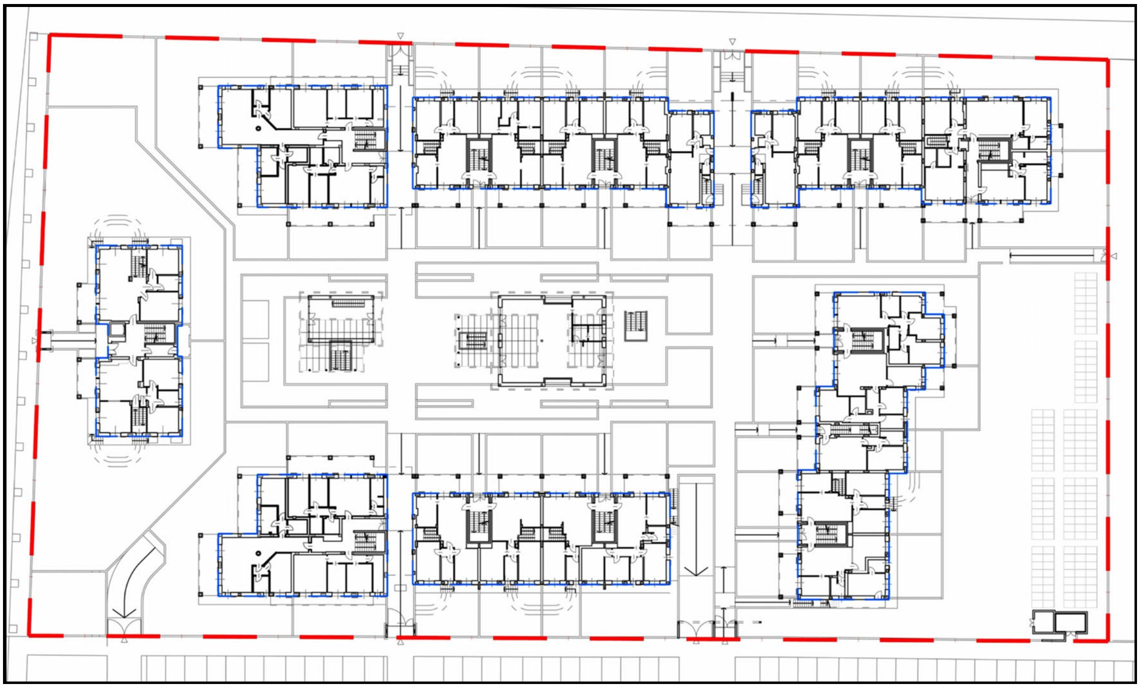

Fig. 1 Groundfloor plan. Site perimeter (*red line*). Building perimeter (*blue line*)

as nZEB. From the architectural and construction point of view, these buildings could be considered as a quite common residential settlement, built in a new urban development on the margins of a little town not far from Milan; the on-site energy production through photovoltaic modules and a borehole heat exchanger could be considered the only evident variance from an usual low-energy residential building (energy class A). The load-bearing structures are made of reinforced concrete, with the lightening brick blocks in the slabs of the residential parts. The perimeter walls are made by thermal brick blocks with an external insulation in rock wool panels; even the internal partitions are in brick with traditional plaster composed of cement, clay and sand. The roof structures are made of glue-laminated wood; pitches are insulated through rock wool panels and a multilayer reflective insulation composed of several aluminium sheets alternated with expanded polyethylene layers; the finishing pitch surfaces are in concrete tiles. All the windows and the external doors are made by PVC profiles, with high insulation performance double glazing, while the skylights on the roofs and the internal doors are made of wood. The winter heating, the summer cooling and the domestic hot water production are assured by a single thermal plant, run by a central heat pump that takes advantages from the horizontal borehole heat exchanger built

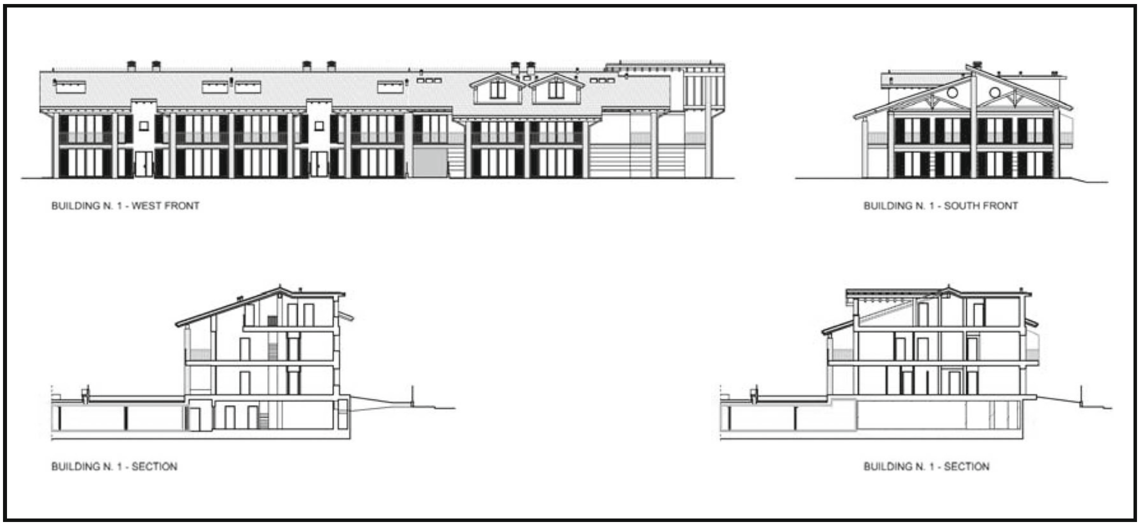

Fig. 2 The West and South fronts and two sections of the Building no. 1

Fig. 3 View of the courtyard

under the underground basement. There is also a mechanical ventilation system to dehumidify the apartments when the cooling system is operating. All the common services are fed with electric power that is partially produced through the polycrystalline silicon photovoltaic panels installed on the roof and on the other structures built in the northern garden. The photovoltaic installations are able to provide the total energy requirement of the heating plant and about 50 % of the energy needs for the domestic hot water production that are higher than the heating requirement, as reported also by Blom et al. (2011) about other low-energy buildings. Although the use of methane is standard in Italian residential buildings, this complex has no connection to the municipal gas pipeline and all devices are powered electrically only.

After the analysis of the main characteristics, we are able to define this residential complex as a nearly zero-energy building of II category, according to Marszal et al. (2011), since the energy production is located partially on the building footprint (photovoltaic panels on the roofs and horizontal borehole heat exchanger inserted in the foundation slab) and partially within the building site perimeter (photovoltaic panels installed in the garden). This classification also derives from the use of on-site renewables, like sun and geothermal heat. Certainly, it does not fully comply with the ZEB concept since about half of the energy requirements for the domestic hot water production is provided by the national electricity grid. For this reason, this residential complex is classifiable only as a nearly zero-energy building, not a full-ZEB, and the main consequence of this aspect is that the operative energy consumption has a positive value and cannot be counted as "zero". The electrical consumption due to the domestic appliances and lighting are not included in the zero balance, as described by Marszal, but we can state that some apartments are equipped with private photovoltaic panels to partially supply this need. The apartments provided with private PV systems are located in the second floor and have at least three rooms and the mansard; on the contrary, the smaller units and the ground floor units do not have private electricity production. Each individual system has a power of about 3 kW.

Fig. 4 View of the building no. 1

However, this result can be considered positive because the residential complex is the outcome of a private real estate initiative conducted by a building contractor who set the nZEB goal without any regulatory constraint, since the settlement was conceived, designed and partly built before the adoption of the Directive no. 2010/31/EU (European Parliament 2010).

6 The methodology

6.1 System boundaries and cut-off rules

According to EN 15643–2:2011 (EN 2011a) and EN 15978:2011 (EN 2011b), the environmental analysis is focused on to the whole complex and its whole life. With regard to the system boundaries, we analysed all the building elements within the property line and we excluded from the assessment only minor components for which we were not able to obtain enough data. The following Sect. 6.3 describes the data collection process and the analysis of each life cycle stage.

From the point of view of the geographical boundaries, we consider the construction and the use of the building on the basis of the site and we measured the impacts of transport from the producers to the building site. We excluded from the evaluation the impacts caused by the transport of the people involved in the construction process and the burdens of the design and managing activities. In a from cradle to gate scenario, the information about the energy mix of the building components included in the database were not modified since it was not possible and out of the research scope to complete the full analysis of each specific building product. We took into account all the stages of building life: materials production, materials transport, building site activities including transport, materials for maintenance and their transport, building operation and end of life; we excluded only the building site activities during maintenance and final demolition because of a lack of literature data. About the time boundaries, the study was conducted in the years 2011–2012 so all the information about the production and the construction process was gathered at the same time of the construction or slightly later, since the complex was built from 2008 to 2012. Although in most cases the lifespan is set as 50 years, as reported by Sartori and Hestnes (2007) and Berggren et al. (2013), we consider that 100 years was more appropriate to the Italian context and to this type of building. However, a few other authors consider credible a longest scenario: 100 years (Mithraratne and Vale 2004; Gustavsson and Joelsson 2010) and 80 years for Peuportier (2001).

From the point of view of the cut-off rules, we decided to consider all the building components and the building activities but, as prescribed in the reference rules (EN 2011a; EN 2011b) and suggested by Marszal et al. (2011), the energy consumption is dependent on the inhabitants' behaviours and the impacts due to the home furnishings were not considered, with the exception of the non-removable elements, such as the bathroom fixtures. The system components are usually not involved in the assessment but we believe that their environmental burdens are not negligible because of their number. For this reason, we acquired data about pipes, ducts, tanks, valves, heating pumps and boilers of the mechanical systems and about cables, ducts and PV modules of the electric and photovoltaic systems. We excluded from the analysis only the minor components that we were not able to identify, like pumps, actuators, controllers and switches of the heating and the electric systems or the displays of the home automation system. Since we considered the majority of the system components, we believe that the influence of the exclusion of these few small elements is negligible in the evaluation of the total amount of the consumed materials.

6.2 Functional unit

Since every building has its own characteristics, the only possibility to compare the environmental profiles of different case studies consists in setting as a functional unit the same service provided in the same time span. Coherently with this assumption, we chose the space unit and the time unit: 1 m^2 of net floor area in 1 year (1 m^2y). This unit of measure allows us to compare the operative energy to the other phases since the net floor area for residential use is equal to the floor area of the heated spaces. We present the final results related to the functional unit but also as a total amount, with the aim of highlighting the size of the environmental burdens. As a reference area, we selected the net floor area (4036 m^2), but we have to bear in mind that in this case study, the total amount of usable area, including ancillary spaces and garages, is double. We consider the net floor area as the space unit because it represents the main goal of the building: to produce inner spaces suitable to live in. Moreover, focusing on the net floor area allows us to put the focus on the relationship between main places and ancillary spaces that varies depending on the building typology.

6.3 Environmental indicators

We managed all the quantitative data concerning the buildings through Excel spreadsheets, and the environmental assessment has been carried out with the software SimaPro 7.3.2. The environmental data were acquired in the Ecoinvent 2.2 database, while we described the results of the evaluation with the indicators of the EPD2008 method (global warming potential (GWP100), ozone layer depletion potential (ODP), photochemical oxidation potential (POCP), acidification potential (AP), eutrophication potential (EP) and non-renewable energy resources (NER)). We chose this set of indicators because it is defined in the EN 15643–2:2011 (EN 2011a).

6.4 Data collection and analysis

The study involved the environmental impacts caused by the building whole life. With regard to the production phase, we took into account all the building materials and components, gathering the specific information about their quantities and characteristics. As a matter of fact, the environmental assessment was based on the inventory of materials which was filled out through the examination of two type of documents: first of all, the invoices paid by the construction company that financed the entire real estate activity; secondly, the building site reports with the accurate description of the construction operations and the amount of the materials consumed, compiled by each subcontractor every month. In addition, many specific details were acquired thanks to the construction project drawings, developed by designers and manufacturers, and a large number of product data sheets. During the analysis of the construction documents, we gathered all possible information about each building product: main characteristics, consumed amount, price, location of the production site and, where possible, means of transport (see Sect. 6.4.1). The whole transport impacts were considered, tracing the itineraries of the raw materials and the semi-finished components, starting from the first production sites to the building site, through the intermediate production steps (see Sect. 6.4.4). The construction phase was also considered: we identified the energy for the main operating machines, the consumable materials as wood or concrete and the removal and the disposal of building site waste divided into debris and recyclables (see Sect. 6.4.5). With regards to the use phase, we took into consideration the consumption of electricity which could not be satisfied from the on-site production through the photovoltaic plant. We included the heat pump consumptions and the domestic hot water production, but we were not able to calculate the electricity requirements for the common areas lighting (see Sect. 6.4.6). Moreover, some maintenance activities were hypothesized on the basis of the service life of the main components; these data were acquired from the component manufacturers and from the experience of the developer, who had

Table 2 Main characteristics of the residential complex

Location: Rodano, Milan, Italy No. of buildings 4	Floors underground, two floors, mansard floor		Apartments 61	
Net floor area 4036 m^2	Ancillary spaces total floor area 4037 m^2		Garage floor area 3300 m^2	
Inaccessible compartment area 1800 m^2	Year of design 2006–2008		Year of construction 2008–2012	
	Building no. 1	Building no. 2	Building no. 3	Building no. 4
Apartments	16	12	29	4
Net floor area	1047 m^2	699 m^2	1905 m^2	385 m^2
Gross floor area	1485 m^2	991 m^2	2701 m^2	546 m^2
Gross heated volume	6536 m^3	4124 m^3	13,045 m^3	2170 m^3
Perimeter surface of the heated volumes	4724 m^2	3217 m^2	6769 m^2	1363 m^2
Shape factor (S/V) coefficient (1/m)	0.72	0.78	0.53	0.63

Structures: reinforced concrete, lightening brick blocks in slabs. Roofs: pitched roofs with glue laminated timber structures and rock wool insulation. Perimetral walls: thermal brick blocks with rock wool external insulation. Internal walls: bricks with traditional plaster composed by cement, clay and sand. Windows: PVC on the facades and wood on the roofs; high insulation performance double glazing. Systems: central heat pump for heating, cooling and domestic hot water production; central mechanical ventilation system. All systems are electric. Renewable energy systems: polycrystalline silicon PV panels on roofs and on independent structure in the garden; horizontal borehole heat exchanger inserted in the foundation slab

been working on the maintenance of residential and office buildings for many decades (see Sect. 6.4.7). Finally, the end of life scenarios of the construction materials were also described but the impacts of the building dismantling were not calculated, due to the impossibility to gather enough data (see Sect. 6.4.8).

6.4.1 Data collection and analysis: the production phase

With regard to the production phase, we collected the quantitative e technical data of building materials subdivided into eight categories, according to the main function performed in the building (see Table 3):

- Structures: it includes all the structural components in concrete, steel, bricks and wood; the lightening polystyrene blocks and the lightening brick blocks inserted in the slabs are also part of this category;
- Masonry: it includes the bricks used both for the vertical envelope and for the internal partitions;
- Insulation: it includes all the insulation materials consumed in the construction, but the lightening polystyrene blocks of the predalles slabs were inserted in the first category because their function is connected to the structural scope; the insulation sheaths of the heating and domestic hot water systems were included in the last category because they are parts of the systems;
- Plaster: it includes all the materials consumed for plaster, both on the internal partitions and on the external side of the walls;
- Waterproofing: it includes all the waterproofing materials;
- Windows: it includes all the materials for windows such as PVC, wood, steel and glass;
- Systems: it includes the components of the mechanical, electrical and photovoltaic systems;
- Finishes: it includes the interior and exterior floors made in stone and ceramics, the finishes surfaces for walls such as tiles, the railings and fencings, the roof finish components and the bathroom fixtures.

6.4.2 Data collection and analysis: the gap between the materials quantity in design and construction

The quality of the data that can be collected and, consequently, the reliability of the evaluation are deeply affected by the moment (during design, construction or use) and the circumstance (in cooperation with designers and builders or not) in which the evaluation is carried out. Since the decisions concerning the building components are taken during the construction details development, an assessment based on the final design only refers to the materials and technologies to be used, however does not specify the characteristics of the products that will actually be employed in construction. On the contrary, if the assessment is based on building site reports, or even better on the compilation of the inventory during the construction phase, it may take into account both the actually consumed amount and the specific data (weight, density, production process, production place). In this way, it is possible to measure also the construction scraps. According to the case study,

Table 3 All construction materials

	Unit	Quantity	km	Notes
Materials for structures				
Additive	kg	956	21	Additive for concrete
Bricks	kg	872,253	317-240-98-77	Lightening bricks blocks in slabs
Cement	kg	3,448,444	268-45	Cement for concrete production
Concrete	m^3	279	317-91-21	Prefabricated elements (beams, pedralles slabs, stairs)
Expanded polystyrene	kg	6027	78	Lightening EPS blocks in predalles slabs
Inert	kg	25,275,055	86-12	Inert for concrete production
Polypropylene	kg	133	9	PP fibres inserted in concrete
Steel	kg	1,133,793	415-317-220-192	Reinforcement bars
Stone	kg	2,900,340	47-41-33-27	Crushed stone under foundations
Wood	m^3	209	425	Glue laminated wood for roof structural elements
Wood	m^3	183	425	Solid wood for roofs
Materials for masonry				
Bricks	kg	2,227,178	309-240-144-98	External and internal walls
Concrete	kg	396,864	49	Concrete blocks for underground internal walls
Materials for insulation				
Adhesive	kg	900	144	Adhesive for insulation panels
Aluminium	kg	1422	40	Insulating reflective membranes
Expanded clay	kg	13,440	14	Underfloor insulation
Expanded polystyrene	kg	10,610	144-21	Insulation for underground spaces
Glass fibre	kg	1398	328-21	Acoustic insulation
Polyethylene	kg	11,585	155-42	Expanded polyethylene for acoustic insulation
Polypropylene	kg	213	40	Insulating reflective membranes
Polyurethane	kg	398	235	Insulation for underground spaces
PVC	kg	232	328	PVC profiles for external walls insulation
Rock wool	kg	81,712	1416-1259-830-503	External and internal walls and roof insulation
Wood fibre mineralized	m^3	111	235	Roof insulation
Materials for plaster				
Adhesive ready-mixed mortar	kg	132,525	328	External walls
Cement ready-mixed mortar	kg	1,848,432	113-61	Internal walls
Lime	kg	5883	21	
Sand	kg	432,870	20	
Materials for waterproofing				
Bentonite ready-mixed mortar	kg	19,574	342-74	Waterproofing mortar
Bitumen	kg	3600	21	Liquid bitumen
Cement ready-mixed mortar	kg	21,971	342-74	Waterproofing mortar
Polyethylene	kg	1570	247-54	Waterproofing membranes
Polypropylene	kg	2171	169	Waterproofing membranes
Primer	kg	1290	74	
PVC	kg	538	342	Junctions
Sheath anti-root	kg	15,315	74	
Sheath bituminous	kg	29,122	74	
TNT	kg	336	47	

Table 3 (continued)

	Unit	Quantity	km	Notes
Materials for windows				
Aluminium	kg	280	309	
Glass	m^2	1257	346-309	
PVC profiles	kg	10,647	1468	
Steel	kg	7378	1468-309	Reinforcement profiles
Wood	m^3	5	672	Glue laminated wood
Wood	m^3	2	309	Solid wood
Materials for systems				
Materials for mechanical systems				
Air treatment	n.	12	30	Mechanical ventilation system
Aluminium	kg	33	263	Ducts in mechanical ventilation system
Brass	kg	809	30	Globe valves in heating and hot water systems
Cast iron	kg	5716	30	Valves in heating and hot water systems
Ceramics	kg	6122	725-320	Bathroom fixtures
Concrete	kg	3478	20	Tanks
Electric boilers	n.	12	30	Hot water production
Expanded polystyrene	kg	5387	30	Insulation of underfloor heating
Glass wool	kg	198	30	Silencers of mechanical ventilation system
Methacrylate	kg	1980	354	Bath tubs
Plasterboard	kg	384	30	Ceiling radiant heating panels
Polyethylene	kg	30,288	371-30	Pipes for water supply, drainage, underfloor heating, irrigation, borehole heat exchanger, fire systems
Polyurethane	kg	225	50	Insulation of water tanks
PVC	kg	852	37	Drainage pipes
Rubber	kg	1134	37	Pipe insulation
Steel	kg	13,195	37	Pipes and tanks for heating, water, sanitary and fire systems
Steel galvanized	kg	42,450	50	Pipes for heating, water and sanitary systems, ducts in mechanical ventilation system, shower tray
Materials for electric and photovoltaic systems				
Aluminium	kg	4448	757	PV systems structures
Copper	kg	8818	152	Electric cables
Galvanized steel	kg	13,313	152	Ducts for electric cables
Inverter	n.	28	1077-732-580	PV systems
Polycrystalline PV modules	m^2	692	1399	PV systems
Polyester	kg	773	757	PV systems structures
Polyethylene	kg	2521	152	Ducts for electric cables
PVC	kg	9018	152	Sheath of electric cables
Steel	kg	24,974	556-37	PV systems structures
Materials for finishing				
Concrete	kg	198,073	45	Roof tiles
Copper	kg	15,084	263-71	Gutters and pluvials
Lead	kg	1012	309-263	Roof elements
Porcelain tiles	kg	219,020	195	Internal floors
Steel	kg	20,504	37	Railings
Steel galvanized	kg	60,610	271-174-33-26	Fencings
Stone	kg	386,976	9200-366	Courtyard, external and staircase floors
Wood	m^3	15	41	Solid wood for internal floors

some materials have been taken as a model to demonstrate the gap between the amount calculated from the design drawings and the quantities obtained from the purchase invoices (see Table 4).

6.4.3 Data collection and analysis: the materials quantity of the precast components

The achievement of a building takes place both through the on-site processing of construction materials, which have undergone a first level of production inside the factories, and through the installation of precast components. These are installed by way of simplified procedures that usually involve limited consumption of materials and therefore generate, on the whole, little amounts of environmental impact in the construction stage. The installations on building site are almost entirely attributable under the sole item of labour, on which superimpose a share of electric energy consumption. By contrast, the majority of the environmental impact related to these components derives from their respective stages of production and transport. In this case study, we identified some precast components, of which we acquired the quantitative data through the construction design documents elaborated by the manufacturers, the product data sheets and the building site reports prepared by the subcontractors. These components were prefabricated beams and stairs, windows and devices for mechanical and electrical systems. The materials quantities of prefabricated structural elements are reported in Table 5.

6.4.4 Data collection and analysis: the transport phase

The assessment of the building products transport from the factories to the site has been characterized by many difficulties because they are often marketed by wholesalers or by companies that undertake only the assembling or the final processing. For this reason, those who are responsible for the materials supply very rarely know the location of the production sites, and in some cases, they only know the name of the final assembler. We conducted a thorough and very punctual research with the aim to trace all the itineraries of semi-finished components and building materials; we acquired all useful information needed from invoices, shipping notes, technical and sales offices of the suppliers. In the cases of insulation and bricks, the builder purchased several products from the same manufacturers, made in different factories: it was possible to identify the right production places through the product codes mentioned in the invoices (the distances are specified in Table 3).

6.4.5 Data collection and analysis: the construction phase

The energy consumptions due to construction activities, the production of some materials used for site preparation and the disposal of construction waste were assessed on the actual data acquired through the building site documents (see Table 6). Electrical energy, potable water and energy for the main operating machines (multiplying the number of work hours for the average consumption of fuel oil) have been inserted; the ancillary materials, boards and planks of solid wood and polyethylene sheets for materials protection and electric cables installed for lighting and the provision of motive power were considered. Three different categories of waste were accounted for the soil of excavation, the debris of bricks and mortar arising from the demolition of the partition walls for the creation of the system traces and the recyclable waste arising from the packaging used for the transport of materials and semi-finished products. The latter group is composed of solid wood of crates and pallets, paper and cardboard, polyethylene sheets and pieces of polystyrene foam used to protect the more fragile materials: they were consigned for incineration with energy recovery.

6.4.6 Data collection and analysis: the energy consumptions in the use phase

The energy behaviour of the buildings was dynamically simulated by the design team to correctly size the photovoltaic installations. The energy analyst adopted the Italian rules (national level: L. 10/1991 and D.Lgs 192/05; regional level: DGR VIII/5018 and DGR VIII/5773; UNI rules: UNI 5364, UNI 10349, UNI EN ISO 13788) to set the reference climate conditions and he chose the softwares Autodesk Ecotect Analysis to define the solar radiation of the buildings and

Table 4 Gap between the materials quantity in design and construction

	Design	Construction	Variation	Percentage
Brick blocks for building nos. 1, 2, 3	820 t	808 t	−12 t	−1.5 %
Brick blocks for building no. 4	69 t	82 t	+13 t	+16 %
External insulation on facades	31 t	26 t	−5 t	−16 %
Structural elements of roofs	203 m^3	209 m^3	+6 m^3	+3 %
Floorboards and little joists of roofs	174 m^3	183 m^3	+9 m^3	+5 %
Insulating reflective membranes	4963 m^2	5200 m^2	237 m^2	+5 %

Table 5 Total materials quantities of prefabricates structural elements

Type	Length/pieces	Steel	Concrete	Bricks
REP—Cls beams	878 m	41 t	98 t	–
REP—Tr beams	1021 m	21 t	–	–
RAFTILE beams	476 m	9 t	–	5 t
Stairs	n. 60	157 t	435 t	–
Total		228 t	533 t	5 t

EnergyPlus to model the energy behaviours of the buildings. All the information about the operative consumption were collected by the design documents and the calculation report of the energy analyst. The heating and cooling system of the complex is totally electric and the total amount of its energy requirement is satisfied by the on-site electrical production. The domestic hot water is supplied by an electric central heater, which requirements are fulfilled by the photovoltaic system for only 43.5 %; the remaining amount is feed by the Italian electricity grid: for this reason, this complex can be classified as nearly-ZEB and not as full-ZEB. In the analysis, we did not take into account the energy consumptions concerning the lighting of common areas, because we were not able to gather the needed information, and the energy consumption of the daily activities of the inhabitants, because they are influenced by the specific habits (Table 7).

6.4.7 Data collection and analysis: the maintenance phase

The buildings under examination were designed with high energy performance and with the aim to be placed at the top end of the housing market. Therefore, the care of the technical design and execution, the choice of high-quality components and the great attention in construction suggest the possibility to maintain a good overall performance with reduced replacement activities. According to the Final Report of the "BLP Durability Assessment" (BLP 2005), most building components have a service life close to 60 years, with the exception of toilets, windows and electric devices which have a lifespan of 35, 30 and 25 years. The table of lifespan scenarios, jointly prepared by the associations of tenants and property owners in Switzerland (MV and HEV 2005), reported lower timeframes included between 30 and 40 years. The characteristics of the buildings under evaluation and the experience of some consulted industry players push to believe that the first replacements of the building components will be made after 50 years, excluding any activity of modernization of the interior spaces for aesthetic reasons or associated with some changes in the property, as they are not dependent on the components' durability. For this reason, the assessment considered a scenario of useful life close to the whole building lifespan, which corresponds to 100 years, for structural elements, external walls, internal partitions and system distribution networks. On the contrary, the façade insulation, the whole roof package with the exception of the structural elements, the under-floor heating system and the floors inside the apartments, the sanitary facilities in bathrooms and the photovoltaic modules are expected to be replaced after 50 years. The windows with PVC frame could theoretically last 100 years if subjected to regular maintenance, but, as a precaution, we consider the substitution after 50 years. The assessment of the maintenance activities considers the components' production (see Table 8), trans- port and the end of life of the waste materials whose quantitative data are equal to the corresponding

Table 6 Building site items

	Unit	Quantity	Notes
Materials for building site managing			
Copper	kg	175	Electric cables
Polyethylene	kg	1687	Protective sheets
PVC	kg	215	Sheath of electric cables
Wood	m^3	160	Solid wood boards
Waste			
Debris	kg	272,750	Bricks, cement, mortar, tiles, stone
Land excavation	kg	16,521,469	
Expanded polystyrene	kg	6445	Recyclable, polystyrene from packaging
Polyethylene	kg	214,980	Recyclable, protective sheets from packaging
Wood	kg	180,585	Recyclable, solid wood from packaging
Energy			
Electricity	kWh	272,950	
Fuel	kg	12,174	
Water	m^3	430	
Scaffolding	kg	266,830	Considered only for transport impacts

Table 7 Energy consumptions in the use phase

	Building no. 1	Building no. 2	Building no. 3	Building no. 4
Gross floor area	1485 m^2	991 m^2	2701 m^2	546 m^2
Gross heated volume	6536 m^3	4124 m^3	13,045 m^3	2170 m^3
Heating requirements	13 kWh/m^2y	14 kWh/m^2y	14 kWh/m^2y	19 kWh/m^2y
	19,305 kWh/y	13,874 kWh/y	37,814 kWh/y	10,374 kWh/y
Cooling requirements	39 kWh/m^2y	32 kWh/m^2y	37 kWh/m^2y	24 kWh/m^2y
	57,915 kWh/y	31,712 kWh/y	99,937 kWh/y	13,104 kWh/y
Domestic hot water requirements	76,679 kWh/y	54,886 Kwh/y	142,445 kWh/y	27,468 kWh/y
Production of electrical energy from PV panels	27,023 kWh_e/y	17,943 kWh_e/y	52,592 kWh_e/y	7590 kWh_e/y
Electricity needs from the electricity grid	17,066 kWh_e/y	13,545 kWh_e/y	29,826 kWh_e/y	9958 kWh_e/y
Supply of the heating requirements by PV panels	100 %	100 %	100 %	100 %
Supply of the hot water requirements by PV panels	52 %	46 %	55 %	21 %

elements taken into account in the production phase analysis; the impacts of the small substitutions are excluded together with the building site operations. With regard to these components, it should be noted that the maintenance work involves the use of the same typology of materials installed during the construction, but these data are to be considered purely indicative because after 50 years, it might be possible to adopt completely different components.

6.4.8 Data collection and analysis: the end of life scenarios

The quantitative data correspond to the total amount of the building materials included in the production phase. In the analysis, we hypothesized that at the end of their life, the buildings will be demolished and the materials will be carefully separated. The environmental impacts linked to the building site activities were excluded due to a lack of literature data. As end of life scenarios, the recycling was hypothesized for almost all the materials (inert materials, metals, plastics), including the impacts until the sorting plant; in some cases, the energy recovery through waste incineration was considered (wood, bitumen, polystyrene).

7 The assessment results

The environmental impacts were assessed both with reference to the production of building materials and considering the life cycle phases of the whole residential complex. Detailed results are presented in paragraph 7.1 and 7.2.

7.1 The production stage results

As described in the paragraph 6.4.1., the substances involved in the production stage were subdivided into eight main categories according to the main function in the buildings: structures, masonry, insulation, plaster, waterproofing, windows, systems and finishes. Due to the characteristics of the building complex, its geometry, its extension and the presence of the underground basement, the load bearing structures are the most impactful category of all the environmental indicators (40 to 60 %), while the high impacts linked to the materials for finishes and those for systems were totally unexpected (15 and 12 %) (see Table 9).

The consumption of energy from fossil fuels (NER) for the production of the structural materials is placed around 50 % of the total amount, as shown in Fig. 5; the second category in order of importance is the finishes, which account for 15 % and is similar to the one of systems components, standing at 12 %. The construction of the load bearing structures, both for the underground basement and for the residential spaces, required the production of 28,725 t of concrete, 1135 t of steel reinforcement bars and 390 m^3 of wood. As mentioned above, the impacts due to the other building materials (without structures, systems and finishes components) are greatly lower, so the sum of the embodied energy of interior and exterior walls (6 %), plaster (6 %) and all the insulation (5 %) slightly exceeds the energy consumption due to finishes components. This last result is quite surprising, and it mainly derives from the consumption of 220 t of porcelain tiles to pave all the residential and the service spaces and the use of 390 t of stone slabs to pave the courtyard and the stairwells, which together amount to 60 % of the embodied energy in the finishing category. On the

Table 8 Construction materials for maintenance during 100 years of useful life

	Unit	Quantity	km	Notes
Materials for external insulation				
Adhesive ready-mixed mortar	kg	132,525	328	External walls
Glass fibre	kg	1398	328	External walls
Paintings	kg	550	328	External walls
PVC	kg	232	328	PVC profiles for external wall insulation
Rock wool	kg	25,885	830-503	External walls
Materials for roofs				
Aluminium	kg	1665	40	Insulating reflective membranes
Concrete	kg	196,885	45	Roof tiles
Copper	kg	15,084	263-71	Gutters and pluvials
Lead	kg	520	263	Roof elements
Rock wool	kg	29,291	1416-1259	Roof insulation
Wood	m^3	183	425	Solid wood
Wood fibre mineralized	m^3	111	235	Roof insulation
Materials for windows				
Aluminium	kg	280	309	
Glass	m^2	1257	346-309	
PVC profiles	kg	10,647	1468	
Steel	kg	7378	1468-309	Reinforcement profiles
Wood	m^3	5	672	Glue laminated wood
Wood	m^3	2	309	Solid wood
Materials for systems				
Materials for mechanical systems				
Ceramics	kg	6122	725-320	Bathroom fixtures
Expanded polystyrene	kg	5387	30	Insulation of underfloor heating
Methacrylate	kg	1980	354	Bath tubs
Polyethylene	kg	4786	371-30	Pipes for underfloor heating
Materials for photovoltaic systems				
Inverter	n.	28	1077-732-580	PV systems
Polycrystalline PV modules	m^2	692	1399	PV systems
Materials for finishing				
Concrete	kg	87,202	45	Underfloor substratum
Porcelain tiles	kg	219,020	195	Internal floors
Wood	m^3	15	41	Solid wood for internal floors

contrary, the energy consumption due to the production of windows is limited to only 2 % of the total quantity of energy for the materials production (25 t of glass and 10 t of PVC profiles were consumed). This is because the extension of the transparent surfaces is limited to the minimum requirement according to the Italian legislation (the minimum transparent surfaces must be one eighth of the net floor area of the room) so, the building envelope is mainly opaque.

The production of the materials needed for the construction of the residential complex consumed a total amount of 92,200 GJ of energy from fossil fuels (see Table 9), of which 45,800 GJ for the load-bearing structures, 17,800 GJ for the building envelope, 13,700 GJ for the finishes and 11,500 GJ for the systems. As reported in Sect. 6.2, if we normalized the total consumption with relation to the functional unit (1 m^2y of the net floor area of 4036 m^2), every habitable square metre absorbed 228.2 MJ/m^2y, corresponding to 63.4 kWh/m^2y and almost 23 GJ over a useful life scenario of 100 years. In this case study, the non-residential spaces are very wide; thus, if we take into account both the residential spaces and the ancillary ones (such as attics, terraces, cellars and the common

Table 9 Total impacts in the production stage

	GWP100 t CO_2 eq	ODP kg CFC-11 eq	POCP kg C_2H_4 eq	AP kg SO_2 eq	EP kg PO_{4-} eq	NER GJ
Materials for structures	4991	0.19	2935	10,425	5134	45,831
Materials for masonry	578	0.05	402	1189	415	6033
Materials for insulation	252	0.01	287	999	244	4564
Materials for plaster	503	0.04	235	1110	443	5652
Materials for waterproofing	93	0.02	132	447	104	3249
Materials for windows	88	0.01	104	456	121	1571
Materials for systems	659	0.08	891	3565	2171	11,494
Materials for finishes	960	0.06	731	4833	3233	13,729
Total (whole building/life)	8124	0.46	5717	23,024	11,865	92,123
Total (m^2y) on 4.036 m^2	0.020	1.14 e-6	0.014	0.057	0.029	0.228
Total (m^2y) on 4.036 m^2 [kWh]						63.4

spaces of buildings, with a total amount of 8073 m^2), the normalized energy consumption could be reduced to 31.7 kWh/m^2y.

As far as the other environmental indicators are concerned, we can state that the structural components cause the highest impact on the GWP100 because they are responsible for the emission of about 5000 t of CO_2 eq, corresponding to 61 % of the total emissions (see Table 9). This value is followed by the materials for finishes (12 %) and for system components (8 %), which is more significant than masonry (7 %) and plaster (6 %). It should be stressed that this is the category of impact where the structures have the greater weight, in contrast with finishes and systems which mark minor impacts. The insulating materials have much lower impacts (3 %), while the contribution of waterproofing materials and windows is very marginal, as it is just over 1 %. Over the whole life of the building, the total GWP100 value is 8100 t of CO_2 eq, equal to 2 t per functional unit (1 m^2y of the net floor area of 4036 m^2).

Finally, we can note that the materials for finishes and for systems reach their highest impact on the AP and on the EP, with greater values than the other building materials. The finishes cause 21 % of acidification and 27 % of eutrophication; on the other hand, the system components cause 15 % on the first indicator and 18 % on the latter. This result is mainly due to the use of copper for system components and for gutters and pluvial. Coherently with the maximum impact of systems and finishes category, the importance of building materials in a strict sense is limited to only 18 % on acidification and 11 % on eutrophication.

7.2 The whole life results

The assessment of the whole life of the building highlights that the pre-use phase, which includes materials production, transport to the building site and construction activities, amounted to 56 % on average, as shown in Fig. 6. We note that, even more than in the analysis of the materials

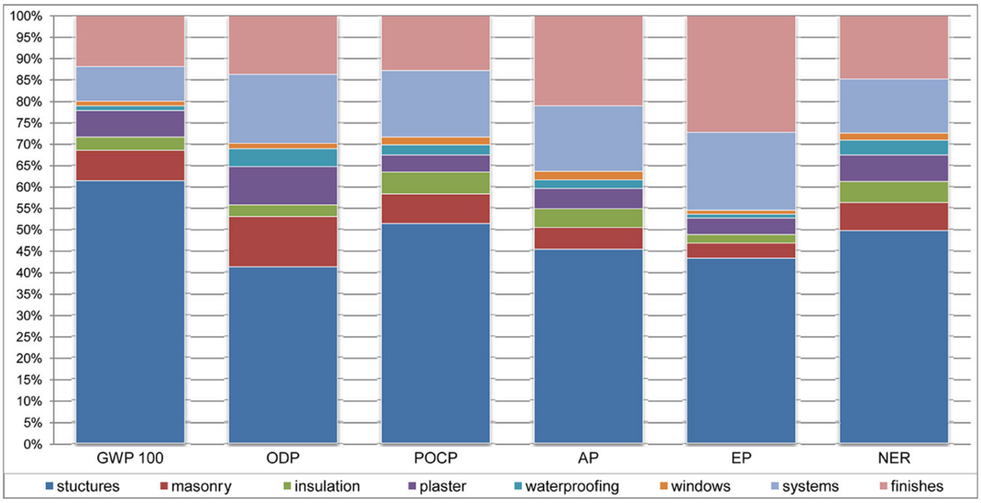

Fig. 5 Impacts in the production stage

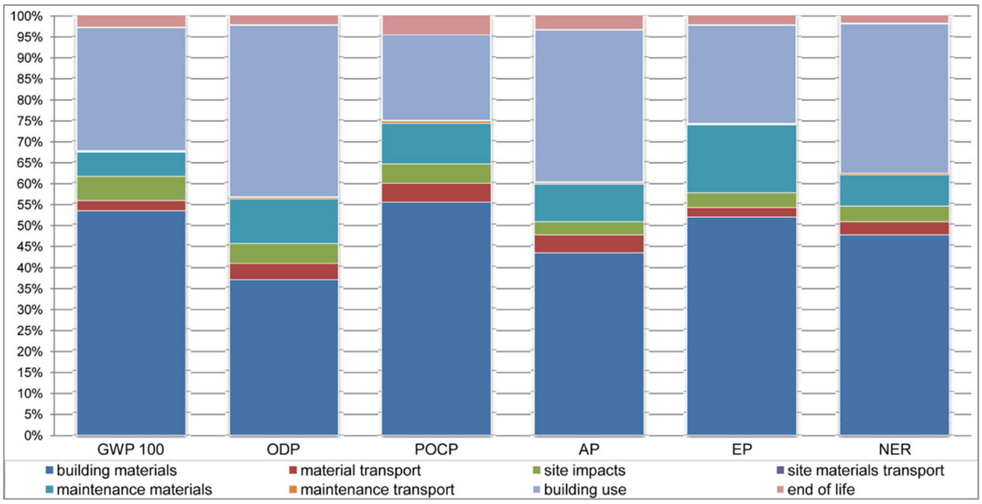

Fig. 6 Impacts in the whole life cycle

production, the results vary according to the considered indicators: the pre-use phase impacts less on ODP (45 %), it has more significance on the consumption of energy from fossil fuels (NER) (54 %) and reaches the maximum values in terms of GWP100 (61 %) and POCP (65 %). On the contrary, the use phase has very high impacts on ODP (41 %) and lower in terms of resource consumption (36 %) and GWP100 (30 %), with an average value of 41 %. However, only 31 % of the total impacts can be ascribable to the building operation. For this reason, if the environmental assessment of this residential complex was shrunk to the operational consumption, only one third of the real impacts would be taken into account. Cuéllar-Franca and Azapagic (2012) and Gustavsson and Joelsson (2010) also state that in nearly zero-energy buildings, the use stage impacts are severely reduced to 35 % of the total, compared to about 80 or 90 % of standard buildings. In Sartori and Hestnes (2007), the embodied energy is declared to be 46 % and in Citherlet and Defaux (2007), the NER is 50 %, but the assessment set-up does not completely coincide. We can also point out that in many case studies, the impacts of the construction phase are not included because some authors considered this value very limited, for instance between 1 and 3 % (Blengini and Di Carlo 2010; Gustavsson and Joelsson 2010; Junnila 2004). On the contrary, in this case, the impacts caused by the transport of semi-finished products to the construction site and the impacts of the construction process on average are more than 7 % (we collected specific data from building site documents).

The operational energy consumptions after 100 years are due to the electricity supplied from the electricity grid to cover the hot water requirements not provided by the PV installations, since they produce the energy for HVAC and only 50 % of the domestic water needs. The operational consumption amounted to 69,300 GJ, that corresponds to 47.7 kWh/m^{2}y (see Table 10); the emissions of greenhouse gases correspond to 4500 t CO$_2$ eq, that are 11.1 kg of CO$_2$ eq/m^{2}y. Finally, the total consumption of non-renewable resources, after 100 years of life, may be listed in 193,950 GJ, equivalent to 133.5 kWh/m^{2}y, normalized on the functional unit (1 m^{2}y of the net floor

Table 10 Total impacts in the whole life cycle

	GWP100 t CO$_2$ eq	ODP kg CFC-11 eq	POCP kg C$_2$H$_4$ eq	AP kg SO$_2$ eq	EP kg PO$_{4-}$ eq	NER GJ
Construction—materials	8124	0.46	5717	23,024	11,865	92,123
Construction—transport	369	0.05	468	2275	512	6046
Construction—building site	891	0.06	497	1715	818	7183
Use (building-related only)	4502	0.52	2124	19,524	5407	69,342
Maintenance—materials	883	0.13	1009	4808	3731	14,619
Maintenance—Transport	46	0.01	56	213	58	758
End of life	439	0.03	484	1803	539	3896
Total (whole building/life)	15,254	1.26	10,355	53,362	22,930	193,967
Total (m^{2}y) on 4.036 m^2	0.038	3.12 e-6	0.026	0.132	0.057	0.481
Total (m^{2}y) on 4.036 m^2 [kWh]						133.5

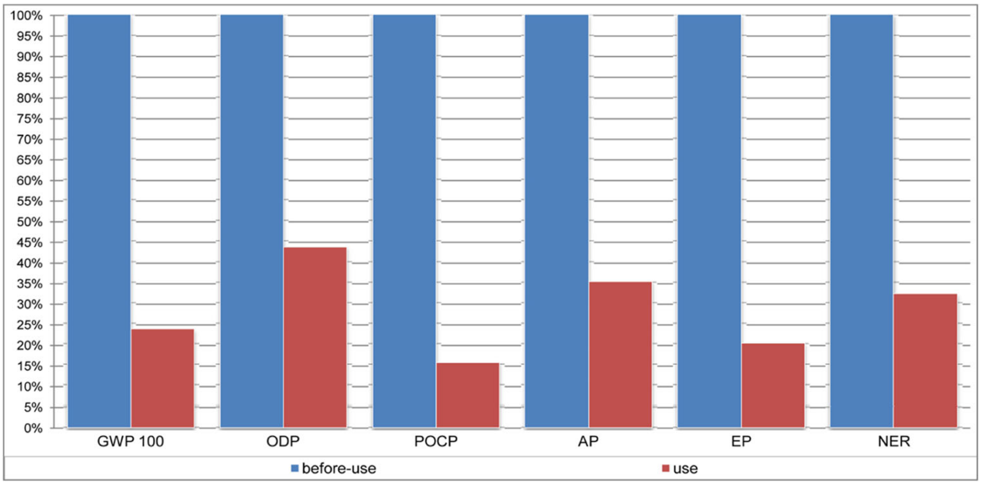

Fig. 7 Impacts after 50 years of life (without maintenance activities)

area of 4036 m^2); the greenhouse gas emissions amount to 15, 300 t, corresponding to 37.8 kg of CO_2 eq/m^2y. Starting from these results, we point out that in a nearly ZEB, the environmental impacts linked to the operation phase are no longer the majority share, but the pre-use phase becomes prevalent. In Fig. 7, the impacts caused by the pre-use phase and those due to the operational phase after 50 years are compared; in Fig. 8, the results of the pre-use phase are compared with the environmental burdens due to the use phase after 100 years (operation and maintenance included).

8 Discussion

The purpose of this paper is to underline the difference between an only energy approach towards the energy efficiency of buildings, as prescribed by the Directive no. 2010/31/EU (European Parliament 2010), and an environmental approach based on a life cycle perspective. For this reason, we apply the life cycle assessment method on a very energy-efficient building (nearly ZEB) to highlight the environmental relevance of the building components and the life stages besides use. We move from the assessment of the operative energy consumption, requested by the EU Directive, to the analysis of the environmental profile of materials and components, over the whole building life.

Besides a lack of ZEB definition both in the scientific community and inside the European rules, we detected much research in which the comparison between the operative energy and the embodied energy are limited to only some life cycle phases or do not consider the whole building components. In this case study, we expanded as much as possible the system boundaries and the cut-off rules to be more comprehensive. About the energy profile, the case study buildings are energy efficient and provided with systems for on-site energy production, but they are not self-sufficient from the energetic point of view. According to the LC-ZEB definition of Hernandez and Kenny (2010), we can consider that the annual production of electric energy from photovoltaic modules is about 105 MWh_e/y, that are equivalent to 228 MWh/y, while the total amount of the embodied energy of the materials and the components needed for the construction and for the maintenance and the energy

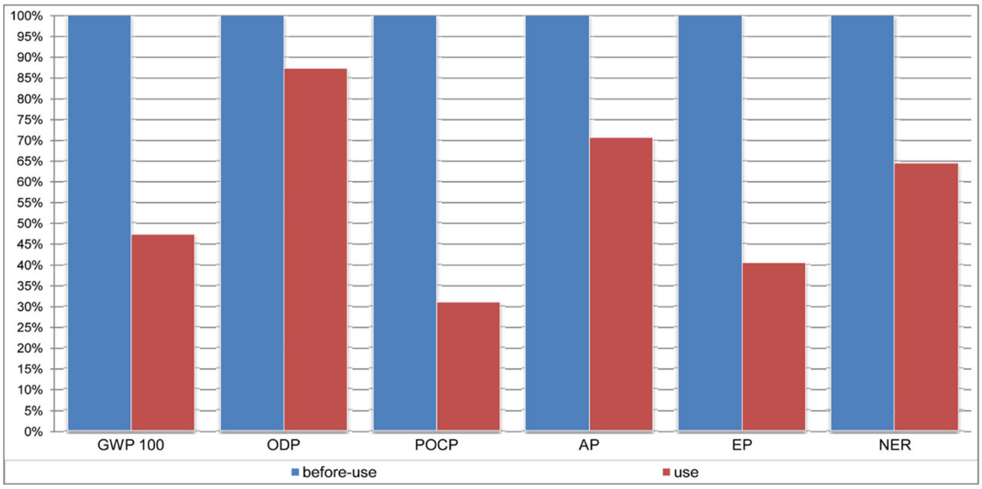

Fig. 8 Impacts after 100 years of life (with maintenance activities)

consumed to operate the building, over a lifespan of 100 years, is about 489 MWh/y. For this reason, the annualized embodied energy (AEE), calculated by the method of Hernandez and Kenny, is 261 MWh/y, so the PV installation will probably be able to cover only 47 % of the energy needs.

The assessment results of the building's whole life highlights that the pre-use phase (which consists of materials production, transport to the building site and construction activities) accounts for 56 % of the total impacts on average (54 % on NER and 61 % on GWP100). The average impact value of the use phase is 41 % (36 % on NER and 30 % on GWP100), but the loads linked to the expected operative energy needs are only 31 % of the total amount; therefore, paying attention to the operative energy consumption seems to address to only one third of the issue. So, the adoption of the LCA as a tool to guide the design choices could help to identify the solution which ensures the lowest overall impact on the whole life, balancing the options of reducing the energy requirements (like improving envelope insulation or system efficiency), the on-site production from renewable sources and the limitation of the impacts due to building components (simpler and more durable).

To better explain this position, we can say that the modelling of the operative energy requirements during the building design with the aim to reduce as much as possible the energy consumption pushes to adopt all the technical solutions that seem to lead to the best possible result in this direction. However, we can point out two issues. First of all, many technical solutions to improve the building efficiency imply the use of a great amount of materials and complex components which are expensive in terms of energy consumed during their production and cause undeniable environmental impacts. If all the analyses are focused on the use phase neglecting a life cycle approach, the actual risk is to bring forward the environmental impacts to the production and construction stages, which are not affected by any control with the exception of the economic aspects; the impacts due to the maintenance activities and the end of life scenarios are also ignored. Secondly, once concluded this life cycle assessment case study, we are able to highlight the considerable presence of equipments which led to very high environmental impacts during the pre-use phase and within the maintenance activities. This condition is typical in the (nearly) zero-energy buildings, but it is not so evident in Passive Houses, because of its ambition for energy self-sufficiency: for this reason, it is required to install many devices for the on-site energy production and for the management of the energy consumption. In addition, this kind of building is generally provided with a sophisticated system to monitor and actively control the indoor environmental conditions with the purpose to optimize the functionality of the technical systems. In recent years, the systems density has steadily increased due to commercial reasons: the devices that are designated for improving the energy efficiency are often flanked by home automation systems (such as in the case study) in order to facilitate the life in, and the management of, the building equipment.

As reported in the previous paragraphs, in this residential complex, the production of the systems materials provoked an average 14 % of the total impacts for the production of the building materials, even if their total weight is quite limited. To this end, it is useful to point out that the systems components are generally produced starting from raw materials which cause greater environmental impacts (such as metals and plastics) than the building materials such as concrete, bricks and wood. Moreover, the industrial cycles necessary to produce the system devices are often more complex and articulated than those of other building materials. We can suggest that the adoption of LCA analysis during the design phase can also allow the optimization of the technical systems, giving the possibility to find the appropriate balance between the materials increase and the consumption reduction.

9 Conclusions

According to a life cycle strategy, a better sustainability level can be achieved by working on the design choices and not only reducing to (near) zero the energy requirements in use. It is possible to carefully select the building components with reduced production impacts or with a longer useful life to limit the maintenance activities. Furthermore, a life cycle approach encourages the analysis of all the building components with the inclusion of systems and materials for finishing, which assessment is often neglected. Therefore, the most environmental efficient solution may be a low-impact building (not only a low-energy one), evaluated over its life cycle and with multiple indicators, rather than a zero-energy one. We can affirm that the Directive no. 2010/31/EU (European Parliament 2010) contains only operative energy prescription, but the new standards enacted by CEN/TC 350 (EN 2010; EN 2011a, 2011b; EN 2012a, 2012b) push towards a global sustainability approach in a life cycle perspective, supporting the environmental evaluation with the economic and the social assessments. Moreover, we can recognize some examples of national certification systems in which the energy evaluation is already flanked by the environmental one, such as MINERGIE-A® (Association MINERGIE® 2011) in Swiss and IBO certification in Austria (IBO 2015). Therefore, some rules and some certification experience already exist, and they could be useful to improve the European Directive, switching it from an energy rule to a rule for the sustainability assessment of buildings.

After verifying the opportunity to employ the LCA to overcome the limits of the European energy policy, we need to think about the evaluation quality. Even if this method concerns the analysis of all the life cycle phases (production, transport, construction, use, maintenance, end of life), many applications in the building sector do not consider some of them. Moreover, in many researches, the information about the characteristics of materials and components and their quantity are gathered from general hypothesis, literature or, in better cases, from design drawings. On the contrary, we collected all the useful data for the evaluation after the construction, through the analysis of building site reports and invoices payed for purchasing materials and services. We recognized some difficulties in the data collection which is very time-expensive: as described, to acquire information about the quantities and the characteristics of the system components, the location of some product sites, the building site activities and their impacts was quite hard. Nevertheless, such in-depth data collection is fundamental because at the end of the analysis, we found that the environmental impacts of some components (for example, systems) and some life cycle phases (for example, transport and construction) are not negligible and are heavier than what reported in literature. Finally, the environmental information about the building products are generally available, although they are often not updated and not related to the specific product when databases are used; on the contrary, the most laborious activity is identifying the right substances and amount in the inventory compilation.

To conclude, adopting LCA as a tool for the building sustainability assessment could be a good chance to overcome the only energetic approach, but a key point is that the success and efficacy of this method depend on how the evaluation is carried out.

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