An overall methodology to define reference values for building sustainability parameters

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Abstract

The paper presents a methodology to define reference values regarding building environmental impacts, energy outputs, and global costs. Four exemplary Italian residential categories were analyzed, focusing on the recent existing stock and on the most common kinds of houses. Buildings were subjected to Life Cycle Assessment (LCA) analyses, through SimaPro software, in order to define specific values linked to the environmental impacts and to the total energy spent. The amount of energy related to the use phase, including heating, domestic hot water, and cooling systems, was estimated by using the energy simulation program EnergyPlus. Building economic performance was analyzed through Life Cycle Costing (LCC) analyses, with the global cost approach. The results showed that the use phase implied the largest contribution to the environmental and energy impacts; instead the pre-use phase was predominant in life cycle costs. Furthermore, since a considerable amount of consistent data was used for this study, the outcomes could be treated as reliable for the definition of benchmarks. For instance, the results indicated that, during the whole life cycle, Italian residential buildings could spend around 140 kWh/m^2, with a production of about 35 kg CO$_2$ eq/m^2 each year, reaching a global cost of nearly 1420 €/m^2.

Keywords: benchmarks, sustainability assessment, energy performance, LCA, LCC

1 Introduction

Since the 1990s, due to the growing attention to sustainability topics, the building sector began to recognize its potential impacts on the environmental, social, and economic spheres. All around the world, laws and policies started to incentivize the use of innovative products and processes to encourage the achievement of a sustainable built environment. Indeed, the improvement of the whole quality of buildings represents a required process on the way to an increasing awareness of both the environment and resource limits. To this aim, the development of methodologies to evaluate the building energy and environmental impacts is a concrete necessity. During the last two decades, many of these methods were developed, showing a considerable utility to assess, rate, and certify the energy and, more generally, the sustainability performance of buildings. Specifically, the construction sector was characterized by the spread of two kinds of sustainability assessment tools. The first group, mainly diffused in the research field, contains those tools that are based on the Life Cycle Assessment (LCA) methodology, such as: Eco-Quantum (Netherlands) [1], EcoEffect (Sweden) [2], Envest2 (U.K.) [3], BEES (U.S.) [4], ATHENA (Canada)[5], SimaPro (Netherlands) [6]. The second group, more common in the practice of the construction world, refers to criteria-based tools, which rely on the evaluation of several criteria, leading to the definition of a total building sustainability score. Among the criteria-based protocols, the most common are: BREEAM (U.K.) [7], LEED (U.S.) [8], CASBEE (Japan) [9], DGNB (Germany) [10], HQE (France) [11]. Furthermore, both the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) worked actively, during the last years, to delineate specific standard requirements related to the environmental and sustainability assessment of buildings. Particularly, the ISO instituted a technical committee, the ISO/TC 59 'building construction', to publish technical specifications on construction sustainability with a focus on the development of indicators for buildings and on the evaluation methods of environmental and economic efficiency. Moreover, the Technical Committee ISO/TC 207, 'environmental management', with the Subcommittee SC 5, 'life cycle assessment', was also instituted, in order to deal with requirements and guide-lines to conduct LCA studies. Instead, the CEN established the Technical Committee CEN/TC 350, 'sustainability of construction works', which aims to define uniform methods for assessing sustainability aspects of new and existing buildings and to develop standards for Environmental Product Declarations (EPDs).

The first generation of sustainability assessment tools accompanied the spread of the building energy certification schemes, which emerged in the early 1990s leading to a wide discussion on the benchmarking of buildings from an energy point of view [12]. Mainly this resulted from the high energy expenditure of the construction sector, which is responsible for around 40% of the global consumption in Europe [13]. Buildings employ energy throughout the whole life cycle, ranging from the construction phase to the use and the end-of-life phases. Many research works [14–18] pointed out how the main amount of the total energy spent during the life cycle is mostly related to the use phase. However, as emphasized by various studies [19,20], the energy consumed during the other life phases, particularly for low and zero energy buildings, is evidently increasing, reaching a high percentage of the energy amount characterizing the entire life cycle. Therefore, the overall energy use evaluation of buildings is gradually spreading beyond the use phase, with the evaluation of the embodied energy, linked to the resource extraction and construction activities, along with the building disassembling and waste disposal. As a result, an approach that takes into account all building stages is manifestly necessary for the definition of the overall sustainability level. In this regard, life cycle-based building assessment tool are needed, as well as the use of recognized objective methods, such as the LCA and life cycle costing (LCC) methodologies.

In the standards ISO 14040 and 14044 [21,22] LCA is defined as: ‘a technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases’. Due to the multifaceted interaction between the built and the natural environment, LCA constitutes a complete and wide approach for the evaluation of the environmental outputs of a building, based on the definition of the specific material and energy flows. LCA was used in construction sector since 1990s, although its application in this sector is still characterized by a lack of standardization, com-pared to other fields. This is not only related to the complexity of a building itself, but also to other specific factors that contribute to make this field unique compared to other processes or products.

In the ISO 15686-5 standard [23] LCC is defined as: ‘a method-ology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope. Life-cycle costing can address a period of analysis that covers the entire life cycle or (a) selected stage(s) or periods of interest thereof’. The aim of LCC analyses on buildings is the estimation of the costs, during the whole life cycle, to be used as input of a decision making or evaluation process. Nevertheless, costs occurring at different periods of the building life cannot be combined directly, due to the varying time value of money. To this aim, economic evaluation methods are needed, such as, the Net Present Value (NPV) technique, which is one of the most used for LCC studies on buildings [24]. Despite the rise of LCC analyses on constructions, mostly related to the cost-optimal approach [25,26], the adoption and application of this methodology in the building sector is still restricted. Finally, for both LCA and LCC, standardized input data and calculation are highly necessary to obtain comparable and meaningful results. In this respect, although numerous attempts for harmonization and normalization were recently done to support the application of these methodologies [27], other investigations are strongly needed.

In recent years, a new approach for defining building sustainability level regarded the attempt to consider energy, LCA and LCC issues in an integrated manner. Indeed, a growing number of building assessment methodologies [28,29] started to include pre-use phase energy analyses, along with environmental and economic evaluations, throughout the entire lifecycle. This new approach clearly required the development of appropriate benchmarks for energy and environmental outputs, as well as for economic performance, with reference to all building life phases. A noteworthy example of the process towards the definition of benchmarks for BNB/DGNB sustainability assessment system is properly illustrated in [30].

In this study, four Italian representative building categories, derived from the recent European project TABULA [31], were analyzed. The aim was to define reference values for several sustainability parameters, such as: total energy, environmental impacts, and global costs. In the next section, the methodology is defined, firstly presenting the case studies and the specific building archetypes investigated. Afterwards, each sub-section introduces the different analyses performed, with a description of the data and the assumptions adopted. Finally, the last section concludes with a presentation of the results and a discussion on the possible implications.

2 Methodology

To evaluate some specific building sustainability-related parameters an overall methodology was developed and its main steps are shown in Fig. 1, which lists: input data, analyses performed, and results pursued.

The analysis of the initial information available in TABULA project led to the choice of some specific data to take into account for the paper aim. The analyzed buildings were chosen in the after-2005 construction period, so that they all presented the typical envelope construction components of the most recent period. Precisely, several building archetypes were built such that they were all characterized by the same shell elements and they were differentiated on the basis of the combination of three variables: the building typology (i); the climatic zone (j); the building systems (heating, cooling, and domestic hot water (DHW) plants) (k). Moreover for each archetype two models were analyzed, Model 1 (M1) and Model 2 (M2), which differ in the evaluation method of envelope thermal bridges. The building archetypes were subjected to three main analyses: (1) 'use phase' energy evaluations, through dynamic energy simulations performed with EnergyPlus software; (2) life cycle impact assessments, with the application of LCA methodology through SimaPro software; and (3) life cycle cost assessments, by means of economical evaluations based on the global cost approach, as suggested in EN 15459 [32]. First, the analyses related to the use phase energy demand were performed and then the results were integrated within the LCA and LCC analyses, leading to the final definition of the investigated specific indicators.

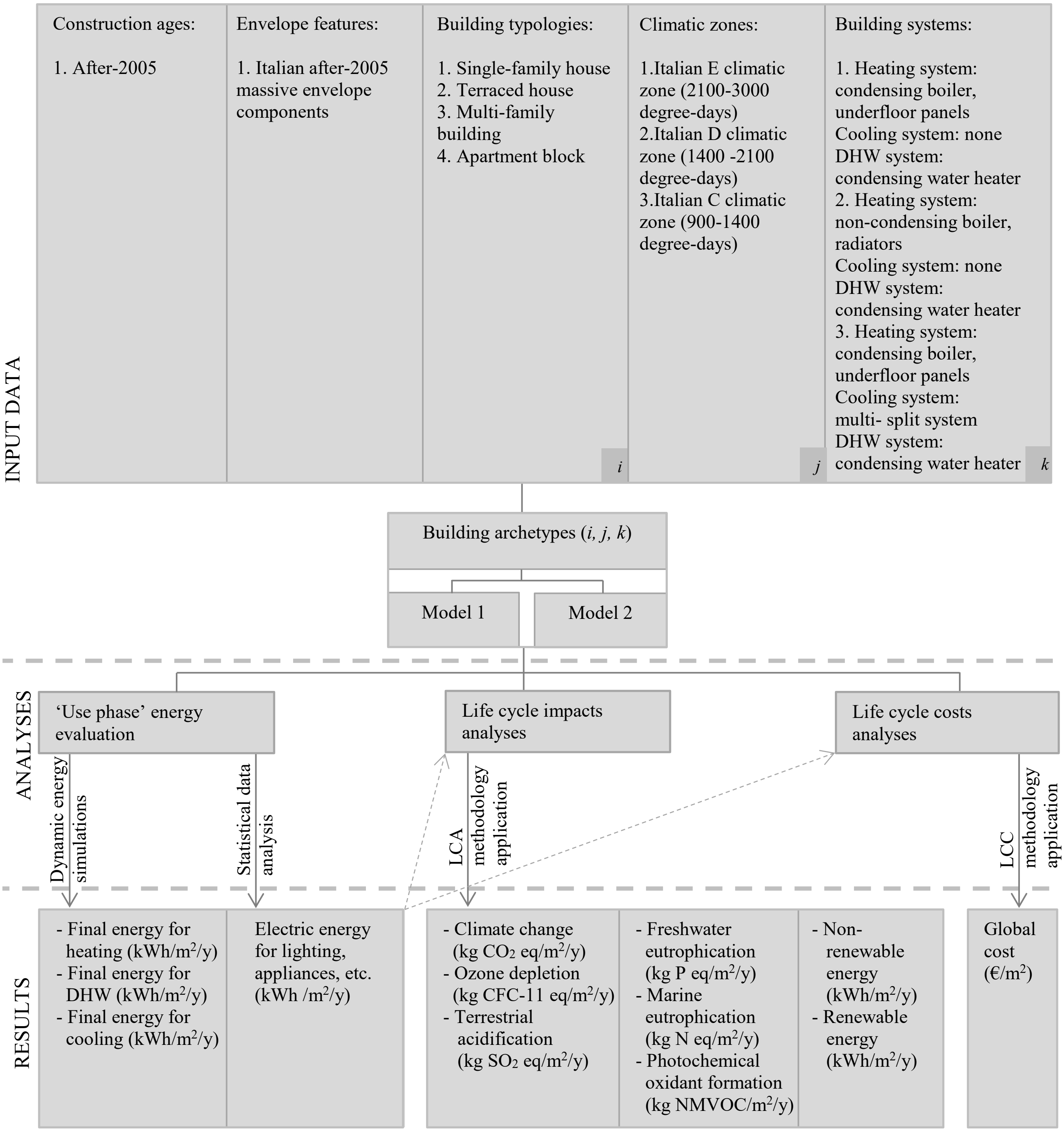


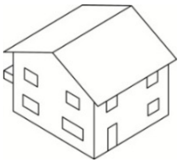
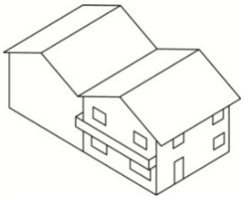
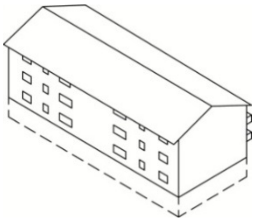
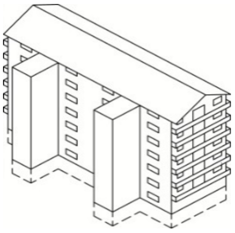
Fig. 1. Methodology phases: input data, performed analyses, and results

2.1 Case studies

The case studies were derived from TABULA project, which provides the definition of the Italian residential building types, aiming to represent specific building categories with their average energy performance and potential savings. The most common kinds of Italian constructions are considered, namely: single-family house (SFH), terraced house (TH), multi-family building (MFH), and apartment block (AB). Buildings are gathered in eight different construction periods (before-1900, 1901–1920, 1921–1945, 1946–1960, 1961–1975, 1976–1990, 1991–2005, after-2005) and are analyzed in a middle climatic Italian zone (2100–3000 degree-days (DD)). The features of the building envelope elements and plants are in accordance to the specific construction age.

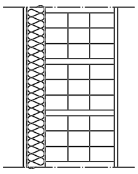
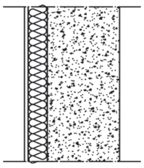
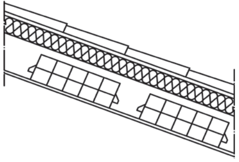
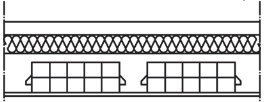
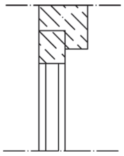
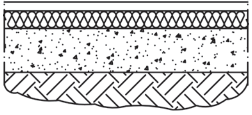
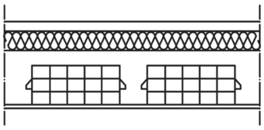
In this paper, the initial data provided by the TABULA project were used in conjunction with some modifications and extensions, in order to define several archetypes. The buildings were drawn from the most recent construction age established in TABULA (after-2005), where they are characterized by the typical Italian massive structures of this period. For the present research, buildings were examined in three different cities, i.e., Turin, Florence, and Bari, belonging to three Italian climatic zones: E zone (from 2100 to 3000 DD), D zone (from 1400 to 2100 DD), and C zone (from 900 to 1400 DD) [33]. The main features about geometrical data, envelope construction elements and building systems were extrapolated by TABULA documentation [31,34]. Otherwise, for missing data, some assumptions were made on the basis of design manuals and standard references [35,36]. The main geometrical data about the analyzed building categories are reported in Table 1.

Table 1. Geometrical features for all building categories

	Single-family house	Terraced house	Multi-family building	Apartment block
				
Number of heated storeys	2	2	3	7
Number of unheated storeys	-	-	1	1
Elevation per floor (m)	2.70	2.70	2.70	2.70
Heated floor area (m^2)	151	127	753	2160
Reference floor area (m^2)	192	165	1256	2968
Gross heated volume (m^3)	622	536	2923	8125
External wall area (m^2)	234	156	646	1699
Window area (m^2)	21.7	15.9	104	270
Shape factor (-)	0.72	0.63	0.54	0.40

The archetypes were all built with the same envelope construction components, whereas thermal transmittance values were modified for the different climatic zones, to comply with the Italian energy standard for buildings (Legislative Decree of the President of the Republic 311/2006 [37], Decree 59/2009 [38]). Envelope element composition and thermal transmittance values, in the three climatic zones, are shown in Table 2.

Table 2. Envelope construction element typologies and thermal transmittance values for all building archetypes, in the three Italian climatic zones

		E climatic zone	D climatic zone	C climatic zone
Exterior wall (W/m^2 K) Honeycomb bricks masonry, high insulation		0.34	0.36	0.40
Walls to unheated space (W/m^2 K) Concrete masonry, high insulation		0.34	0.36	0.40
Pitched roof (W/m^2 K) Reinforced brick-concrete slab, medium insulation		0.74	0.74	0.74
Flat roof (W/m^2 K) Reinforced brick-concrete slab, high insulation		0.30	0.32	0.38
Window (W/m^2 K) Low-e double glass, air filled, wood frame		2.20	2.40	2.60
Slab above ground (W/m^2 K) Concrete slab on ground, high insulation		0.33	0.36	0.42
Slab on unheated space (W/m^2 K) Reinforced brick-concrete slab, high insulation		0.33	0.36	0.42

Furthermore, unlike TABULA project, which considers only one plant typology for each construction age, in the present paper, the archetypes were equipped with three building system types, aiming to exemplify some common Italian typologies. As visible in Fig. 1, Building system 1 comprised an heating system consisting of a condensing boiler (efficiency coefficient $\eta = 0.98$) with underfloor panels, and no cooling system; Building system 2 included an heating system comprising a non-condensing boiler (efficiency coefficient $\eta = 0.89$) with radiators, and no cooling system; Building system 3 was the same of Building system 1, with a cooling system in addition, represented by a direct expansion multi-split system (energy efficiency ratio, EER = 3). For all the building systems, the DHW plant consisted of a single condensing water heater (efficiency coefficient, $\eta = 0.99$) for SH and TH, and of several condensing water heaters (efficiency coefficient, $\eta = 0.99$) for SH and TH, and of several condensing water heaters (efficiency coefficient, $\eta = 0.90$), for MFB and AB.

Moreover, for each archetype, two models were considered for the analyses: M1 and M2. The first model, M1, accounted thermal bridges, as in TABULA project, by means of a percentage increment (15%) of the construction element thermal transmittances, as recommended, for existing building evaluations by Italian energy standards (UNI/TS 11300-1 [39], UNI EN ISO 14683 [40]). Instead, in the second model, M2, thermal bridges were evaluated through the introduction of linear thermal transmittance coefficients, as suggested by the same Italian energy standards for new building assessments.

2.2 'Use phase' energy evaluation input data

To define the energy requirements related to the use phase, all the archetypes were analyzed through the EnergyPlus dynamic energy simulation software. EnergyPlus was used to evaluate fuel consumption of heating and DHW systems, in addition to the electricity for the auxiliaries and the cooling system. Instead, electric energy for lighting and other indoor appliances (fridge, dishwasher, washing machine, etc.) was derived from official statistical data [41]. Regarding climate settings, hourly weather data were derived from the International Weather for Energy Calculation database developed by ASHRAE in 2001. The weather files correspond to a typical meteorological year in the three analyzed locations: Turin, Florence, and Bari. A fixed natural ventilation rate, of 0.3 h^{-1}, was considered. Internal gains were set with a value based on the heated floor area of the building categories. Moreover, internal design temperatures, for both heating and cooling season, were defined on the basis of the indications in UNI/TS 11300-1. The latter standard was also the reference for the setting of the heating season duration, different for each climatic zone. Besides, since there is not any standard recommendation for the cooling season length, its duration was considered as complementary to the heating season one. The energy requirement for DHW was calculated considering a standardized daily specific requirement (l/m^2 day), depending on the heated floor area of the buildings. Table 3 provides information about energy simulation-related parameters, for each building category and climatic zone under evaluation.

Table 3. Parameters for energy modelling of all building archetypes

	E climatic zone				D climatic zone				C climatic zone			
	SFH	TH	MFB	AB	SFH	TH	MFB	AB	SFH	TH	MFB	AB
Heating design temperature (°C)	20				20				20			
Cooling design temperature (°C)	26				26				26			
Air exchange rate (1/h)	0.30				0.30				0.30			
Cooling period in days	183				199				229			
Heating period in days	182				166				136			
DHW requirement ($L/m^2 \cdot day$)	1.37	1.41	1.58	1.60	1.37	1.41	1.58	1.60	1.37	1.41	1.58	1.60
Internal gains (W/m^2)	2.80	3.20	4.30	4.20	2.80	3.20	4.30	4.20	2.80	3.20	4.30	4.20

2.3 LCA analyses input data

This section presents the main data for the application of the LCA methodology, following three essential stages, as defined in ISO 14040-44 standard: goal and scope definition, inventory analysis, and impact assessment.

2.3.1 Goal and scope definition

One of the goals of the study was to evaluate the environmental impacts during the whole life cycle of Italian reference buildings. The LCA analyses involved the following life stages: pre-use phase, including materials production and transport to the building site, in addition to construction on-site processes; use phase, regarding the use of fuel and electricity for heating, DHW, cooling, lighting and appliances; end-of-life phase, including building de-construction/demolition with waste transport, processing, and final disposal. Maintenance and refurbishment activities, such as the substitution of building components, were also considered and included in the pre-use phase, taking into account the additional materials provided. To ensure the comparability of LCA analyses, a functional unit was defined, considering a building life span and a reference area. The lifetime selected in this paper was 50 years, which represents a common value for LCA examinations of residential buildings [17]; instead, the reference area corresponded to the gross floor area, including that of the unheated floors.

2.3.2 Inventory analysis

For the inventory definition, the three main life cycle phases (pre-use, use, and end-of-life) were investigated.

Concerning the pre-use phase, the total quantities of materials constituting building envelope and plants were evaluated and collected, on the basis of the information provided in TAB-ULA documentation. However, given the lack of detailed data, the inventory phase required that the available information were completed with literature data, as listed in Table 4. Moreover, the adaptation of the different building archetypes to the three climatic zones led to slight changes in some material quantities, such as the insulation ones. In this first stage, materials were also associated to: a life span factor (LS), indicative of the number of substitutions required, during the total building life time; a waste factor (WS), representing the percentage of cutting waste generated during the building construction processes. Table A.1, of Appendix A summarizes the amounts of the main materials embodied in envelope and plants, including WS and LS, for the building archetypes of SFH, TH, MFB, and AB, analyzed in Turin and equipped with Building system 3. Data on the life span of building systems were derived from Annex 1 of EN 15459. Furthermore, for envelope element replacements, it was assumed to: repaint external walls after 25 years; substitute windows and external doors after 30 years; replace roof covering after 30 years. Material waste factors were adapted from [15,19], while transportation means and distances to the construction site were defined through LCA guidelines [27]. In particular, building materials were supposed to be transported by lorry and the distances from the production plants to the building site were assumed as: 50 km for concrete based materials and wood, and 100 km for all the other materials. Additionally, energy and diesel, used for building construction activities, were assessed and adapted with reference to literature data [15,18–20].

Table 4. Life cycle phases, sub-phases and data sources

Life cycle phases	Sub-phases	Data source
Pre-use	Building materials	TABULA documentation, technical manuals [31, 34-36]
	Transport	Literature data [27]
	Construction process	Literature data [15, 18-20]
	Maintenance	Literature data and standards [15, 19, 32]
Use	Final energy demand for heating, DHW, and cooling	Calculation with EnergyPlus software
	Final energy demand for lighting and appliances	Statistical data [41]
End-of-life	Dismantling, demolition, recycling/landfill	Literature data [15, 18-20, 43]

The life cycle inventory models were implemented in SimaPro 8 software, with reference to Ecoinvent 2.2 database [42], which contains average values of eco-profiles datasets for material manufacture, energy production, and trans-port systems.

For the use phase, the energy simulation results, based on the input data explained in Section 2.2, were used. Specifically, the annual values were adapted to a life span of 50 years and associated to the fuel and electricity eco-profiles available in Ecoinvent database, with regard to the natural gas and the Italian electricity mix. Furthermore, the amount of water consumed during the use phase was also considered and limited to the DHW requirement, as specified in Table 3.

The end-of-life stage was modelled on the basis of the information available in recent similar studies [15,18–20,43], which include quantitative and procedural data about the end-of-life steps, from the possible building demolition to the final rubble processing. Therefore, an initial selective dismantling stage was considered, regarding recyclable materials, such as windows, doors, and aluminum within plants. Afterwards, a controlled demolition of the building, by hydraulic hammers, was set. Finally, demolition waste disposal was taken into consideration, including transportation to treatment plants and final processing, such as recycling or landfill. Concerning waste handling, materials like steel, concrete, ceramics, bricks, and others were supposed to be almost totally recycled, even though in different stages. For example, lithoid elements were sup-posed to be treated after the building demolition and transformed into recycled aggregates. Instead, as regards steel, the part related to the systems was expected to be recycled after the selective dismantling, while the quantity characterizing structural bars was supposed to be recycled after the demolition process. Furthermore, waste transport data were set considering an average distance from the treatment plant of 15 km for inert materials and of 20 km for recyclable materials, as suggested in [27].

In this paper, the avoided burden approach was adopted, according to which the impact of virgin materials production is avoided by their re-use or recycling.

2.3.3 Impact assessment

According to the ISO 14040 procedure, some indicators of energy and environmental performance were chosen, in order to characterize the building impacts throughout the life cycle.

The Cumulative Energy Demand (CED) assessment method [44] was selected to calculate six indicators: fossil non-renewable energy; nuclear non-renewable energy; biomass non-renewable energy; biomass renewable energy; wind, solar, geothermal renewable energy; water renewable energy. As a result, the comprehensive indicators ‘non-renewable energy’ (kWh) and ‘renewable energy’ (kWh), for the whole building life cycle, were estimated.

Furthermore, in order to evaluate specific environmental impacts, such as emissions to air, land and water, the Recipe method [45] was also applied. Six representative indicators were chosen, namely: Climate Change [CC] (kg CO_2 eq); Ozone Depletion [OD] (kg CFC-11 eq); Terrestrial Acidification [TA] (kg SO_2 eq); Fresh-Water Eutrophication [FE] (kg P eq); Marine Eutrophication [ME] (kg N eq); Photochemical Oxidant Formation [POF] (kg NMVOC).

2.4 LCC analyses input data

Life cycle cost analyses were developed according to the procedure described in the European Standard EN 15459, which calculates the global cost as:

$$C_G(\tau) = C_I + \sum_{j} \left\{ \sum_{1=1}^{\tau} \left[C_{a,i}(j) \cdot R_d(i) \right] - V_{f,\tau}(j) \right\} \tag{1}$$

where CG (τ) represents the global cost referred to starting year τ_0, C_I is the initial investment cost, $C_{a,i}$ (j) denotes the annual cost for component j at the year i (including running costs and periodic replacement costs), R_d (i) is the discount rate for year i, $V_{f,,\tau}$ (j) represents the final value of component j at the end of the calculation period (referred to the starting year τ_0).

As reported in EN 15459, the various costs have to be multiplied by a discount rate or by a discount factor, in order to be actualized to the initial year τ_0. Specifically, the discount rate is used for periodic costs, such as replacement ones, and for the final value of building components; instead, the discount factor is used in the case of annual costs, such as those related to the energy or water consumption. Both the discount rate and the discount factor depend on the real interest rate and on the timing of the considered costs. The real interest rate depends, in turn, on the market interest rate and on the inflation rate, both here considered as constant and set on the basis of the average values of the past ten years recorded by Eurostat [46]. Finally, an annual increase in gas, electricity and water price was also accounted and set to be the same as the inflation rate.

It is worth to notice that the life cycle phases investigated for LCC are not completely homogenous to those of LCA analyses. Indeed, because of the lack of reliable and market-based cost data for demolition and materials disposal, in LCC investigations the end-of-life costs were not taken into account. The general assumptions adopted for LCC and LCA are shown in Table 5.

Table 5. General conditions for LCA and LCC analyses

	LCA	LCC
Life cycle phases	Pre-use phase	Pre-use phase
	Use phase	Use phase
	End-of-life phase	-
Indicators	Climate change (kg CO_2 eq)	Global cost (€)
	Ozone depletion (kg CFC-11 eq)	
	Terrestrial acidification (kg SO_2 eq)	
	Freshwater eutrophication (kg P eq)	
	Marine eutrophication (kg N eq)	
	Photochemical oxidant formation (kg NMVOC)	
	Non-renewable energy (kWh)	
	Renewable energy (kWh)	
Reference unit	Reference floor area	Reference floor area
Calculation period	50 years	50 years
Energy costs	-	Natural gas: 0.60 €/m^3
	-	Electricity: 0.16 €/kWh
Water cost	-	Water: 1.60 €/m^3
Building envelope maintenance costs	-	0.15% of construction cost
Building systems maintenance costs	-	Based on EN 15459
Inflation rate	-	2.3%
Market interest rate	-	4.5%
Gas price rate development	-	2.3%
Electricity price rate development	-	2.3%
Water price rate development	-	2.3%

The economical evaluation of the whole building life cycle regarded the following classes of costs: investment costs, including material providing, transporting, and assembling prices; replacement costs, counting expenses for repair or change building components; running costs, comprising annual costs for periodic maintenance and energy/water costs, related to annual prices for energy and water.

Therefore, the building total global cost was assessed by summing up, during the life span, the initial investment costs, replacement costs, annual maintenance and energy/water costs and subtracting the building component final values at the end of lifetime, as shown in Eq. (1).

Table A.2, of Appendix A presents a summary of all cost categories for the building archetypes of SFH, TH, MFB, and AB, located, in Turin and equipped with Building system 3.

2.4.1 Investment costs

The investment costs were estimated as the sum of the costs for building construction elements and building systems. For each examined archetype, costs were associated to its main classes of technological units, which are provided by UNI 8290 [47]. Investment costs were evaluated by means of a price list containing average Italian costs (VAT excluded) of building materials and components [48]. Furthermore, general administrative expenses and profit for the enterprise were not taken into account.

2.4.2 Replacement costs

Replacement costs, during the calculation period, were evaluated on the basis of the substitution of some building components, over the whole life cycle. Therefore, considering the life span factor of the elements, as already specified for LCA analyses, periodic costs or replacements were defined and then adjusted to their present value, through the application of the discount rate. Furthermore, within this cost category, the final value by the end of the calculation period was evaluated, as specified in EN 15459, by summing up the contributions related to all building systems and components. In particular, the final value was estimated as the remaining life-time of the building components, divided by lifespan and multiplied with the last replacement cost.

2.4.3 Running costs

Running costs were assessed considering two main categories: annual costs related to building maintenance and repairs, including yearly operations for preserving building component and system quality; annual costs of energy for heating, DHW, cooling, lighting and appliances, in addition to the annual costs for potable water consumption.

Maintenance costs were assessed considering different price sets for single and multi-family building categories. Indeed, for SFH and TH, only ordinary maintenance costs of envelope components and building systems were considered. Precisely, costs for maintenance of shell elements were estimated as a percentage, 0.15%, of their initial investment cost, as a usual value for the Italian context [49]. Instead, annual maintenance costs of building system components were evaluated according to Annex A of EN 15459, where they are expressed as a percentage of their initial cost. Instead, for MFH and AB, supplementary costs were added to those specified for SFH and TH. Indeed, due to their condominium management nature, specific costs were considered, in relation, for instance, to the lift maintenance, the common area cleaning, and the building administration. Specifically, these additional costs were estimated as an annual fixed value of 15 €/m^2, as deducted from similar building analyses [49].

Costs of energy and water were estimated by means of available statistical prices, VAT excluded [50]. Therefore, data related to the final energy carrier demand for heating, DHW, cooling, lighting, auxiliaries and appliances were converted into fuel and electricity quantities, in order to define costs for natural gas and electric energy. Similarly, water costs were determined on the basis of the volume of potable water required for DHW, during the use phase.

3 Results

3.1 'Use phase' energy evaluation results

In order to compare the different analyzed building categories, the outcomes were normalized for the heated floor area and showed on annual basis. Fig. 2 illustrates the annual final energy use, disaggregated into heating, DHW, cooling and lighting/appliances/auxiliaries, for both M1 and M2 of single-family house archetypes, analyzed in the three considered cities and equipped with the three building systems.

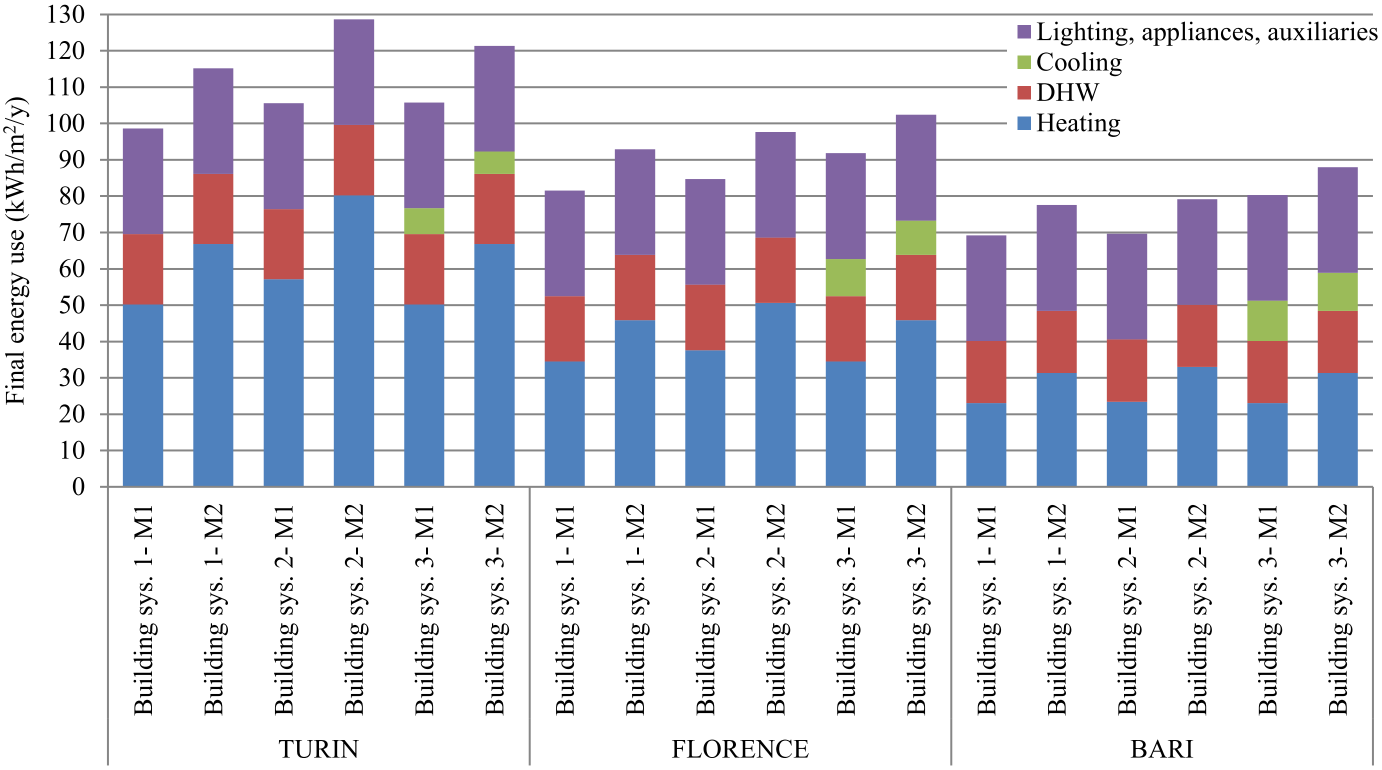


Fig. 2. Annual energy demand- final use, in three Italian cities, for M1-2 of SFH, equipped with Building systems 1-3

The results in Fig. 2 confirmed the standard trend in building energy demand evaluations, which are generally influenced by the different climatic zone where buildings are located. In fact, the highest value of the annual final energy demand, 129 kWh/m^2, was reached in Turin, due to its high value of DD, which caused a higher heating energy demand compared to the other cities. Instead, in Bari, the lowest value of the annual energy demand, 69 kWh/m^2, was achieved, as a result of its low energy requirement for heating, although its warmer summer climate implied the highest cooling energy demand. Moreover, in each climatic zone, the main differences in the results were mostly related to the heating system consumption, which was evidently affected by the way of evaluating the thermal bridges. Indeed, M1 and M2 resulted in a divergence of the annual energy use up to 20%, as a consequence of the different transmission heat flow through the building envelope.

Fig. 3 shows the annual final energy values for M2 of all building category archetypes, equipped with Building system 3 and examined in the three studied cities. Besides the already pointed out result differences in the various climatic zones, it is evident how the outcomes changed from one building category to another. The highest values were reached by the SFH, as a result of its highest shape factor (envelope area/heated volume), in addition to its use of autonomous building systems. Specifically, the maximum value reached among the different building categories was 121 kWh/m^2, instead the minimum and average values were 69 kWh/m^2 and 90 kWh/m^2 respectively. The results obtained in this sub-section represented a fundamental intermediate step for the definition of the sustainability parameter values referred to the whole building life cycle, as illustrated in the following sub-sections. Particularly, as a consequence of the previously described outcomes, M2 was chosen for the illustration of the other indicator results, since it allowed a more accurate and realistic evaluation of the building energy use.

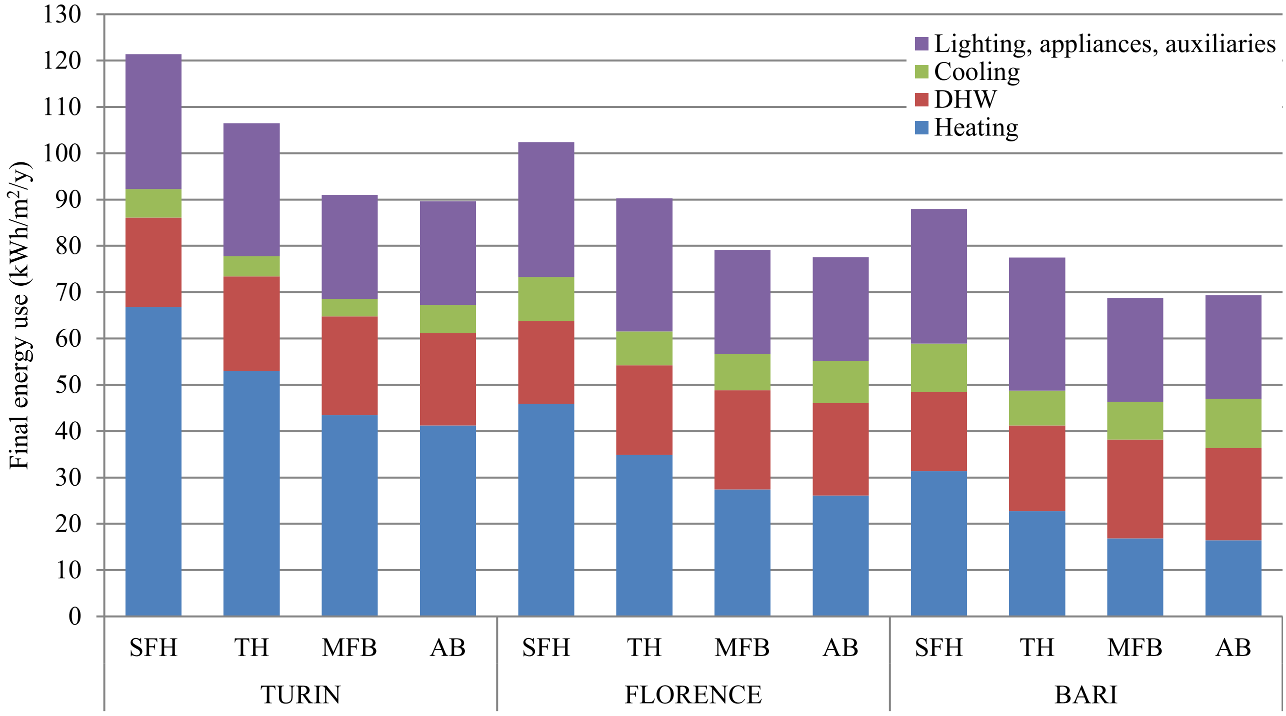


Fig. 3. Annual energy demand- final use, in three Italian cities, for M2 of SFH, TH, MFB, AB, equipped with Building system 3

3.2 LCA analyses results

the specific reference floor area. Specifically, Figs. 4–11 report the results of the analyzed indicators for M2 of all the archetypes, including a grey line to mark the overall average values. As visible in Fig. 4, for all the archetypes, the total non-renewable amount of energy was considerably higher than the renewable one. On average, the percentages of non-renewable and renew-able energy amounts were 95% and 5% respectively. This was due to the major use of non-renewable energy resources for both building materials and use phase energy. Indeed, the analyzed buildings were principally made by traditional materials, such as concrete, bricks and steel, which are dominated by the non-renewable energy component, while typical renewable materials, e.g. wood, represented a minority. Likewise, the use phase energy demand relied mainly on non-renewable energy sources, since heating and DHW systems were supplied by natural gas, while cooling, lighting, appliances and auxiliaries were based on electricity, which, in Italian electricity mix, is mostly produced by non-renewable energy sources.

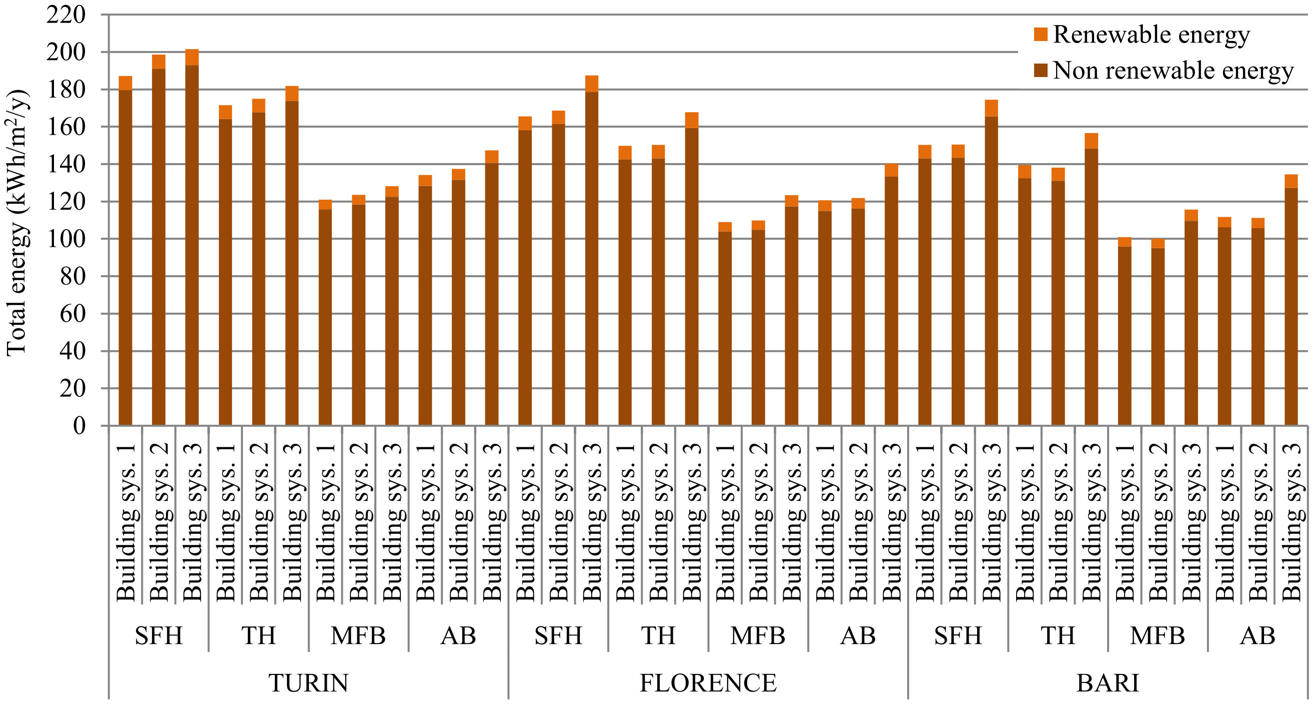


Fig. 4. Total energy indicator, split in the non-renewable and renewable amounts, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

In Fig. 5 it is possible to note that, in the total energy use, the use phase provided the main contribution, on average 75%, while the pre-use and the end-of-life phases contributed with an average of 29% and 4% respectively. This confirmed the trend that characterizes standard houses, as reported in other studies [14–18], where heating-related impacts predominate the whole building life cycle. The end-of-life phase, because of the avoided burden approach adopted, always presented a negative contribution on the results. An overview of the values, obtained for the entire life cycle of all the calculated archetypes, showed an average annual value of 145 kWh/m^2, ranging from a maximum of 200 kWh/m^2 and a minimum of 100 kWh/m^2.

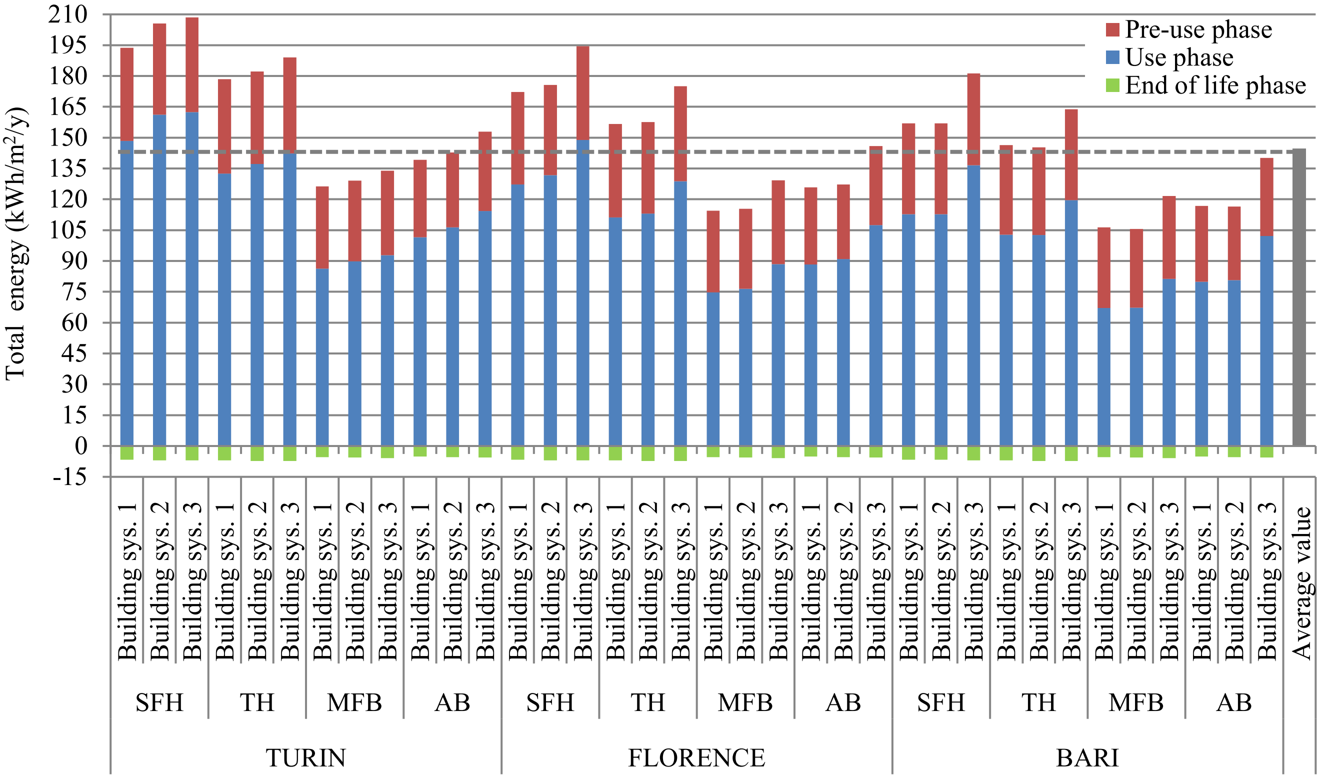


Fig. 5. Total energy in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

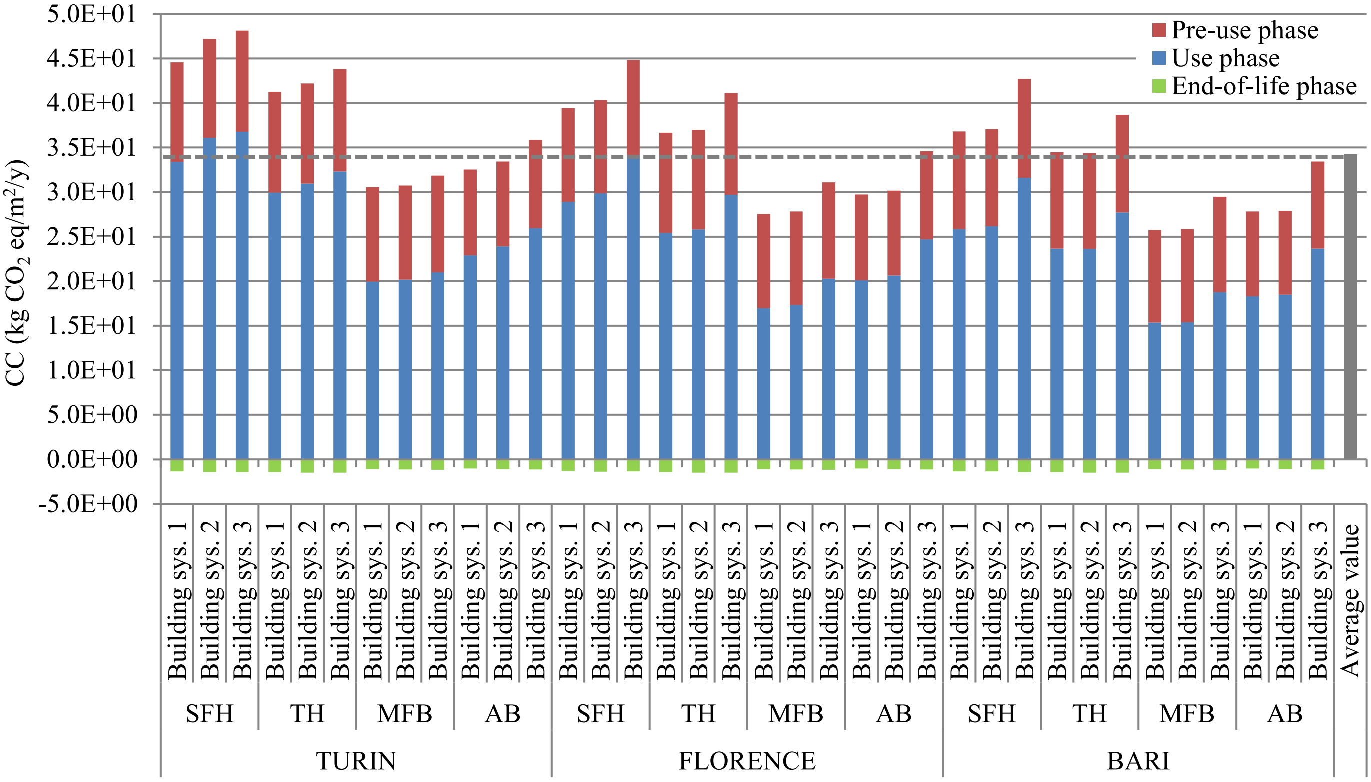


Fig. 6. Climate change (CC) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

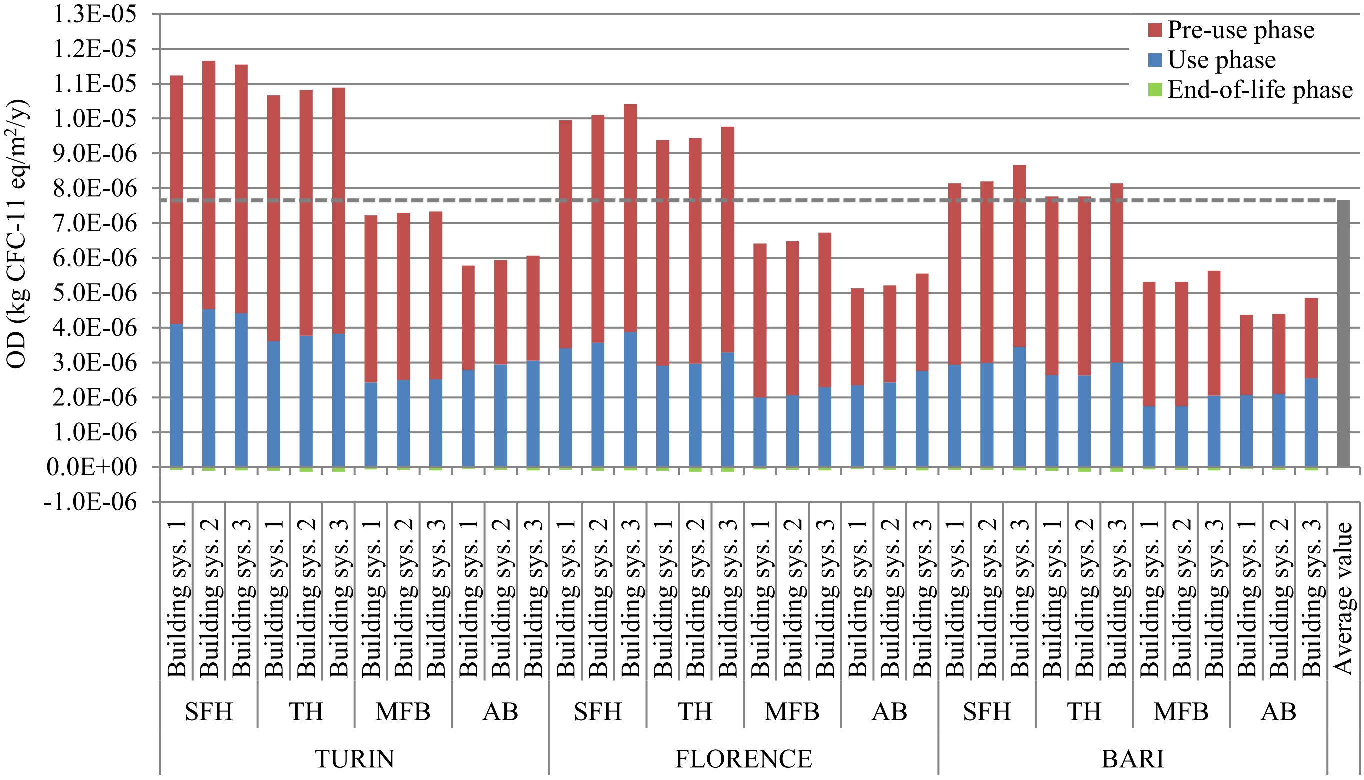


Fig. 7. Ozone depletion (OD) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

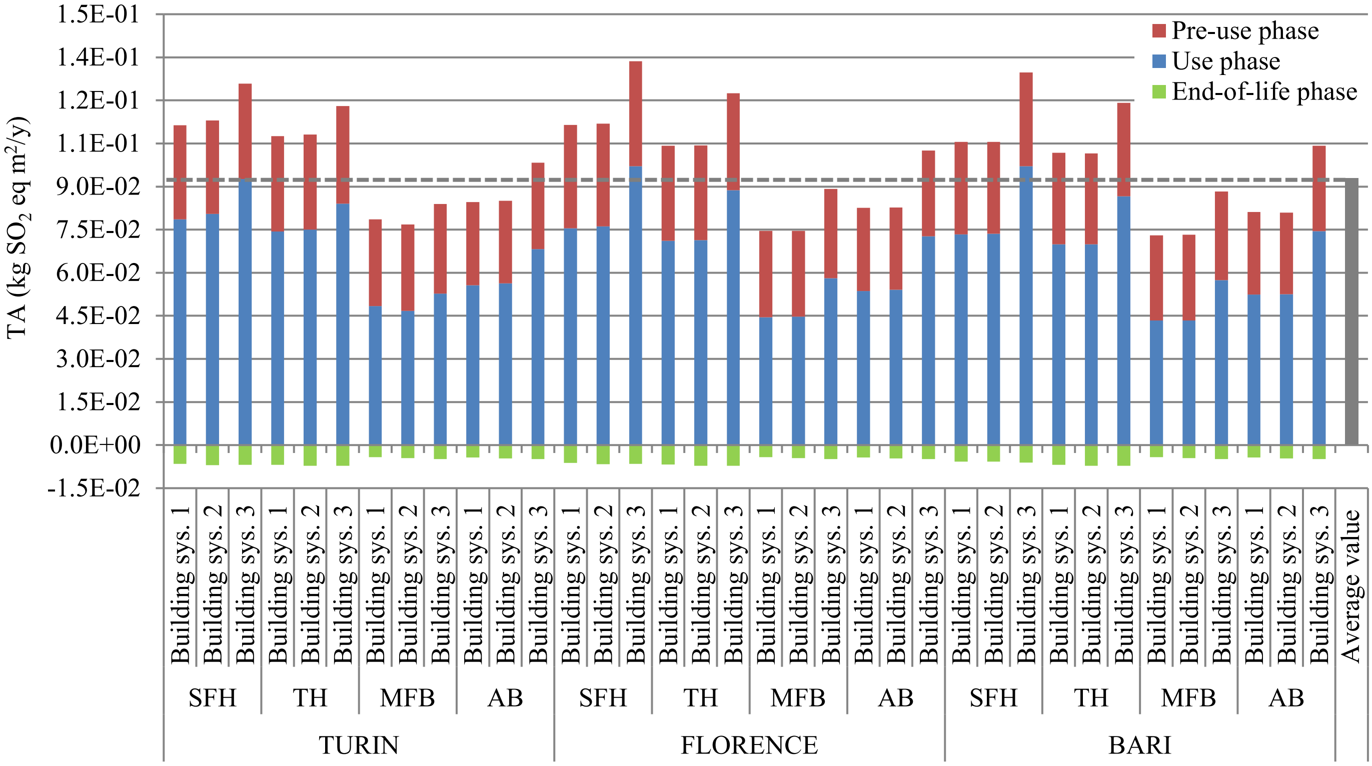


Fig. 8. Terrestrial acidification (TA) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

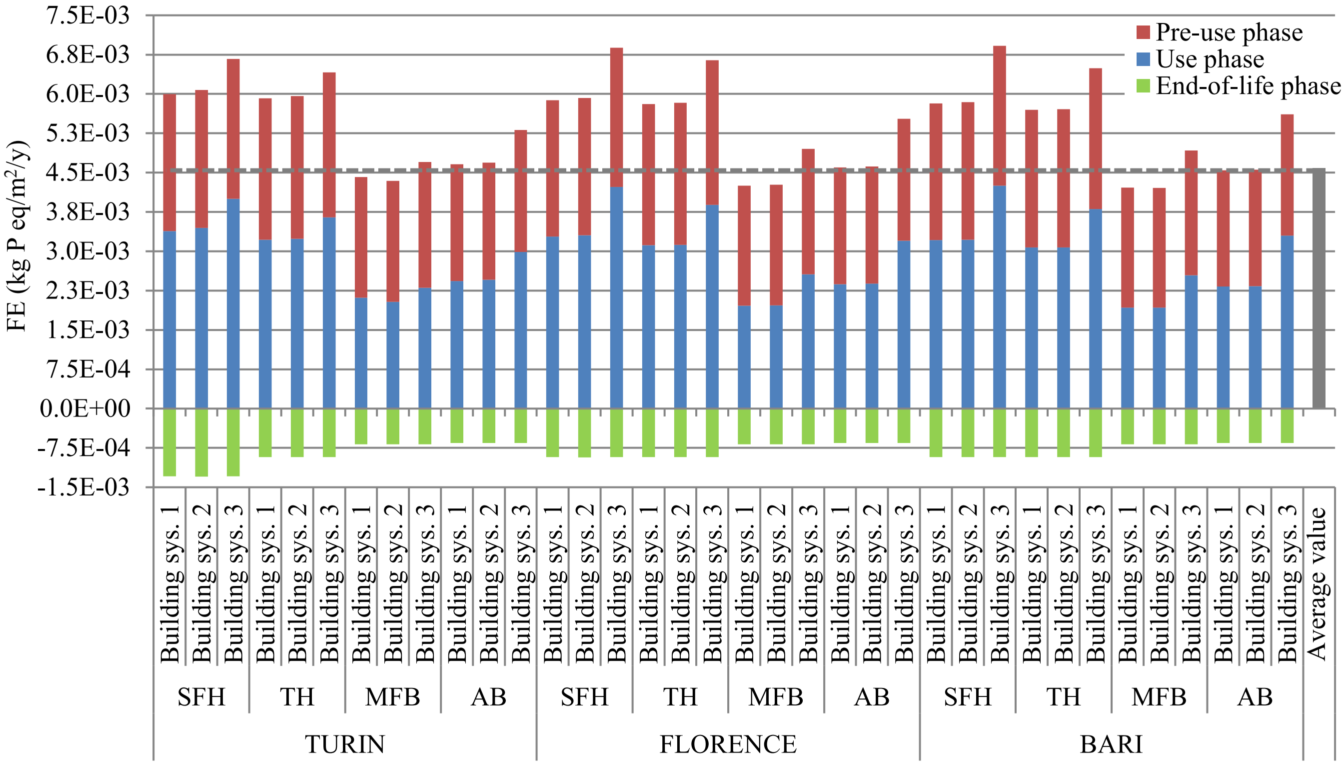


Fig. 9. Fresh water eutrophication (FE) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

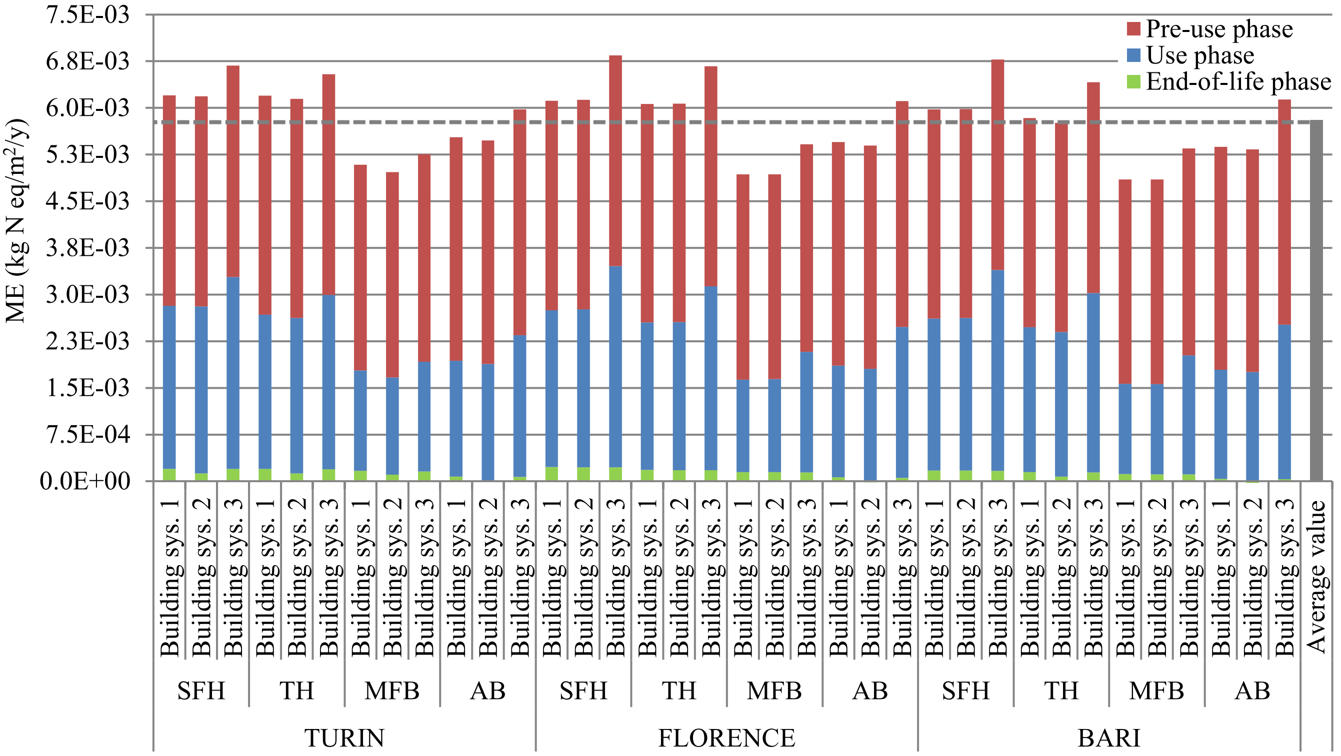


Fig. 10. Marine eutrophication (ME) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

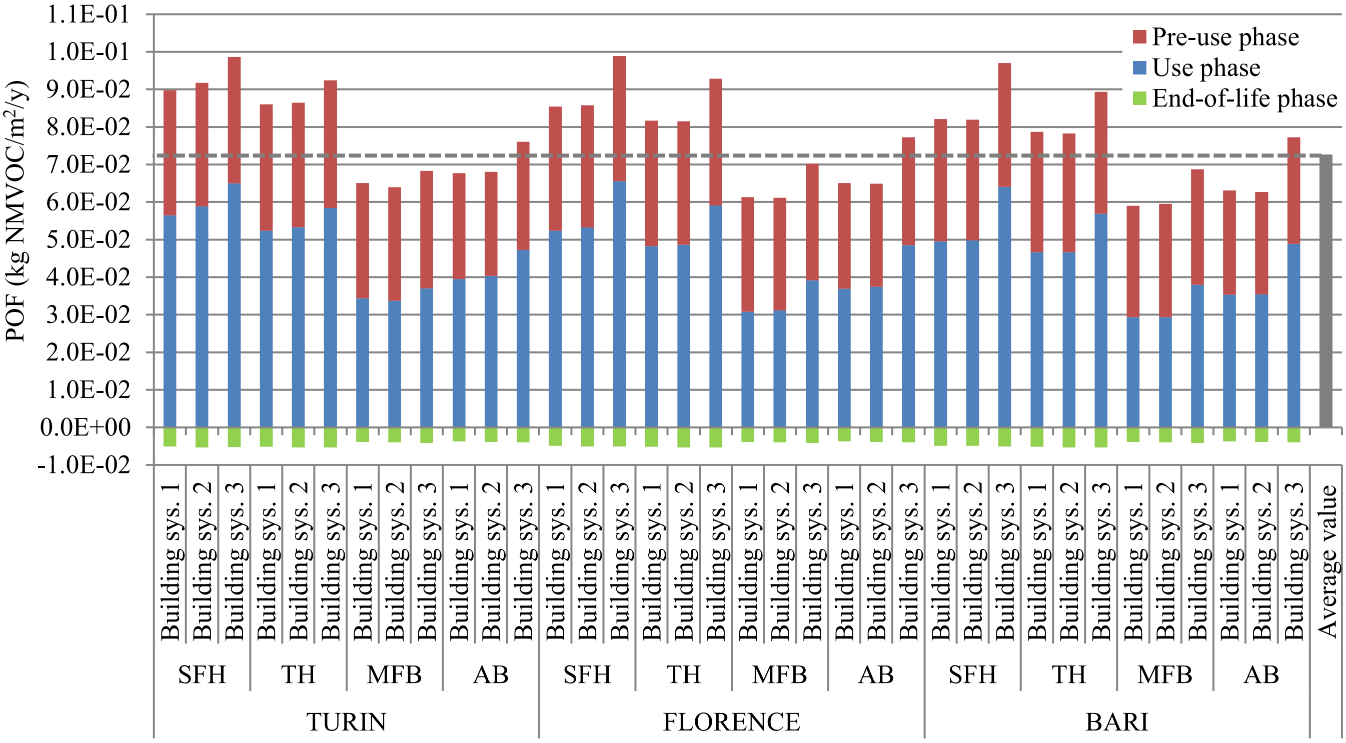


Fig. 11. Photochemical oxidant formation (POF) indicator in different life cycle phases, for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

Table 6 summarizes the average values obtained for the environ-mental indicators, along with the before mentioned energy-related ones, in each building life phase and in the total life cycle. The comparison with other similar studies for the Italian context, although overall more limited [19,20], proved a relatively good agreement of the results.

Table 6. Average values of all the examined LCA indicators

Indicator	Unit	Pre-use phase	Use phase	End-of-life phase	Total life cycle
Non-renewable energy	kWh/m^2/y	3.90E+01	1.05E+02	-5.77E+00	1.38E+02
Renewable energy	kWh/m^2/y	2.65E+00	4.52E+00	-4.84E-01	6.68E+00
Climate change	kg CO_2 eq/m^2/y	1.06E+01	2.49E+01	-1.26E+00	3.42E+01
Ozone depletion	kg CFC-11 eq/m^2/y	4.87E-06	2.90E-06	-9.50E-08	7.67E-06
Terrestrial acidification	kg SO_2 eq/m^2/y	3.15E-02	6.71E-02	-5.65E-03	9.29E-02
Freshwater eutrophication	kg P eq/m^2/y	2.48E-03	2.93E-03	-8.27E-04	4.59E-03
Marine eutrophication	kg N eq/m^2/y	3.44E-03	2.24E-03	1.27E-04	5.80E-03
Photochemical oxidant formation	kg NMVOC/m^2/y	3.11E-02	4.60E-02	-4.55E-03	7.26E-02

The outcomes obtained for the environmental indicators (Figs. 6–11) showed a distinction in the way of being affected by the pre-use phase or the use phase, since the end-of-life provided always a small contribution.

The CC indicator, shown in Fig. 6, was mostly influenced by the bearing structure materials and by the use phase energy consumption. Since all the analyzed buildings were made by the same primary materials, CC values mainly differed for the type and the amount of energy spent during the use phase. In particular, space and water heating represented the leading contributors from this stage, due to the production and the use of natural gas.

As visible in Fig. 7, the OD indicator was more impacted by the pre-use stage than by the use one. Particularly, this indicator was heavily affected by the application of insulation materials, such as expanded and extruded polystyrene (EPS/XPS), largely used in the building archetype envelopes.

The TA outcomes, given in Fig. 8, showed an almost similar influence by the pre-use and use phases. This parameter was mostly linked to production and use of the electricity, as well as of the wall materials used.

The FE results, shown in Fig. 9, were relatively mostly affected by the bearing structure and wall materials. Instead, the use stage mainly contributed with the production and use of electricity, as well as with the water consumption. The latter equally affected the ME indicator values (Fig. 10), which received, a high contribution also by the materials within the building walls, principally by the alkyd paints.

Finally, the POF values (Fig. 11) showed an equal contribution from the pre-use and the use phase, receiving a particular influence from the electricity and the materials in the building envelope.

3. 3 LCC analyses results

The results of LCC analyses were normalized by the calculation period (50 years) and the specific reference floor area. They are shown in Fig. 12 for M2 of all the archetypes, including a grey line to mark the overall average value. As visible, the investment cost category represented the leading component (between 50%and 72%) in determining the final global cost, followed by the maintenance costs, ranging from 8% to 33%. The main differences in the investment costs among the archetypes were connected to the lower price of the radiators compared to the underfloor panels, as well as to the presence of the cooling system. Furthermore, it is important to realize that investments costs exerted no evident influence on the results obtained for the different cities, since the building envelope and system materials had similar quantities within the various climatic zones. Instead, maintenance costs presented evident differences among the building categories, due to the additional maintenance costs considered for MFB and AB. As a consequence, although SFH and TH categories presented highest values of investment and energy costs, MFB and AB showed comparable final global costs, due to their higher running costs.

The energy/water cost set related to the building use phase contributed to the global cost with a significant percentage, from 9%to 19%. Besides, the energy/water cost category represented one of the main contributors in the global cost variations, due to the highly different final energy demand in each climatic zone.

The replacement costs, which concurred with a relatively small percentage to the global cost (from 2% to 9%), were higher for the archetypes equipped with Building system 3 compared to the others, due to the presence of the cooling system, implying also slightly higher maintenance costs.

Overall, the average value reached among the analyzed building archetypes was 1423 €/m^2, instead the minimum and maximum values were 1287 €/m^2 and 1608 €/m^2 respectively. The comparison of the results was made with a similar study [30], referred to the German context, since no other full LCC studies exist for the Italian housing sector, as far as the authors are aware. A reasonable accordance of the results was proved, even if the studies followed different general conditions for the calculation, as for instance in the economic indices.

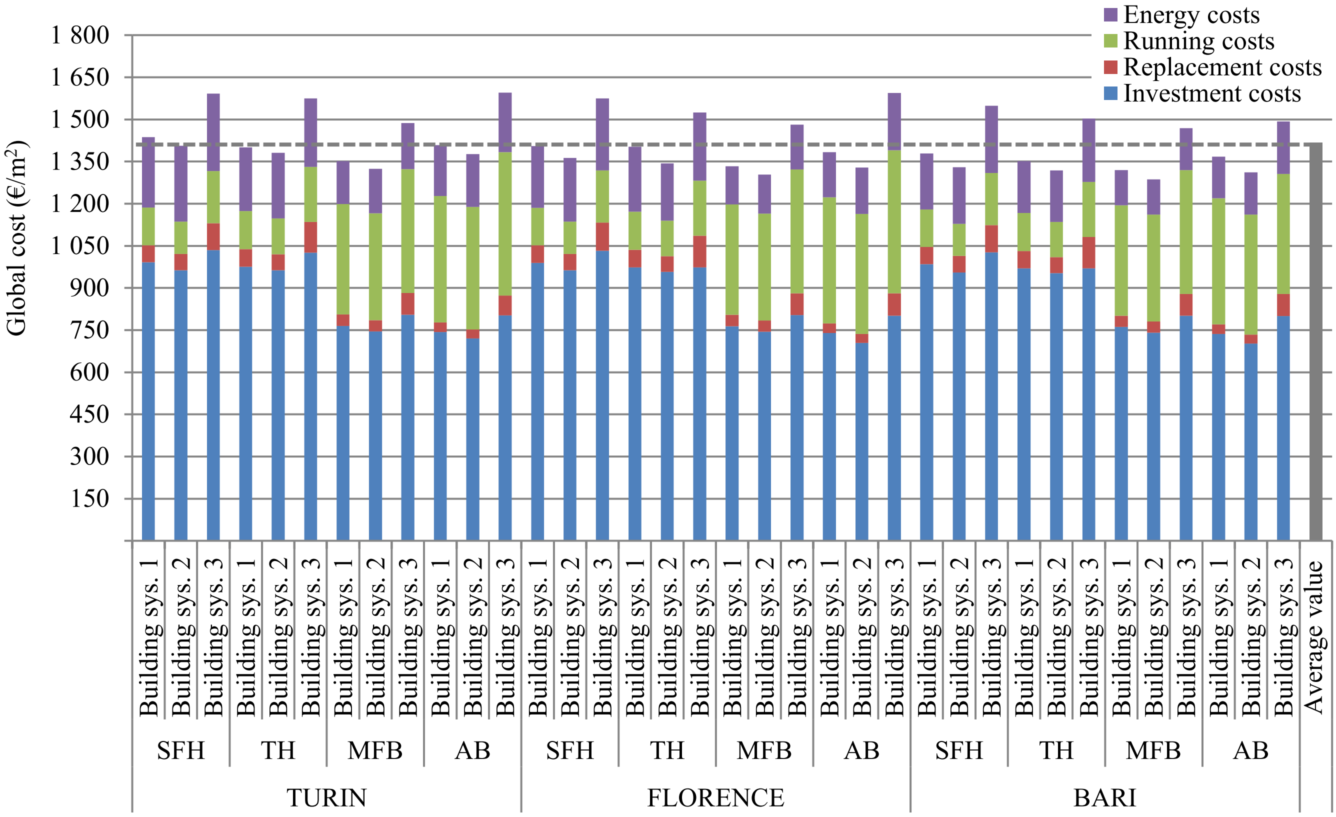


Fig. 12. Global cost for M2 of SFH, TH, MFB, AB, equipped with Building systems 1-3

4 Conclusions

The paper illustrated an overall methodology to define reference values for representative building sustainability parameters. In particular, given the increasing interest in the overall quality assessment of buildings, the research focused on specific indicators, referring to the whole life cycle and representing essential outputs for a complete building sustainability evaluation. Besides, the chosen parameters were analyzed also due to the lack of related limit or reference values, for the Italian context.

The results of this research could be useful for different building stakeholders, such as designers, constructors, owners, as well as sustainability system developers and users. Particularly, since a huge amount of reliable references and statistical data was used for this analysis, the results could be treated as trustworthy for comparison with other studies, energy planning, and decision making. Indeed, significant values, regarding sustainability parameters, were drawn; for instance, the results showed that, during the whole life cycle, Italian residential buildings could spend around 140 kWh/m^2, with a production of about 35 kg CO_2 eq/m^2 each year, reaching a global cost of nearly 1420 €/m^2.

The research provided an effective procedural and operative tool for decision makers in the field of sustainability assessment systems. Specifically, the study illustrated a detailed methodology that could be followed in the definition of the scale of values to be used in benchmarking specific performance indicators. In addition, the reference values arising from the methodology application could be implemented in Italian sustainability rating systems for residential buildings, as soon as the analyzed indicators will be introduced in their structure. Furthermore, the outcomes of the research could be used as a comparison base of environmental, energy, and economic parameters for future similar studies.

The aim of the paper was also to contribute to the reaching of a progressive standardization in sustainability parameters assessment, with the suggestion of some general assumptions and calculation rules. To this purpose, in addition to homogeneous evaluation procedures, recognized life cycle materials inventories, as well as reliable data for construction and use phase costs, are manifestly necessary for future similar analyses.

The research work showed some limitations which could emphasize future study directions. For instance, other archetypes, within the identified building categories, could be analyzed, in order to accurately improve benchmark value reliability. Moreover, even though the analyzed reference constructions were chosen to represent the standard Italian building stock, future analyses could enlarge the research scope, considering different energy demand requirements, as for instance low energy buildings. In this regard, given the stringent law requirements for energy efficient constructions, in a not far future, zero and positive energy buildings will necessary increase, leading to the need of new consistent and appropriate benchmarks for overall sustainability assessments. Finally, bearing in mind the uncertainty up to 20% in energy use investigation results, sensitivity analyses on the benchmark values could be a future important study. Indeed, further examinations are also needed, for instance for economic evaluations, considering e.g., different discount rates or more reliable development rates of the energy prices.

Appendix A.

Table A.1 Material inventory for the pre-use phase of SFH, TH, MFB, AB, equipped with Building systems 3, in Turin

Envelope material	Database entry	Amount (kg)				WF (%)	LS (-)
		SFH	TH	MFB	AB		
Concrete	Concrete, sole plate and foundation, at plant/CH U	68 169	59 952	111 786	148 884	4%	1
	Poor concrete, at plant/RER U	12 519	11 010	20 529	27 342	4%	1
	Concrete block, at plant/DE U	N/A	N/A	147 677	165 453	4%	1
	Concrete, normal, at plant/CH U	180 665	151 177	1 743 398	3 439 911	4%	1
Steel	Reinforcing steel, at plant/RER U	8 487	6 076	42 177	80 660	5%	1
Cement	Base plaster, at plant/CH U	6 669	4 766	32 716	80 195	10%	1
	Cement mortar, at plant/CH U	4 825	4 079	33 883	86 055	6%	1
	Cement cast plaster floor, at plant/CH U	5 93	4 934	50 481	132 736	10%	1
	Light mortar, at plant/CH U	1 943	1 644	8 181	10 896	4%	1
Gypsum	Gypsum plaster board, at plant/CH U	9 670	9 645	55 419	157 790	10%	1
Plastic	Polystyrene foam slab, at plant/RER U	685	490	4 023	8 892	4%	1
	Polystyrene extruded, at plant/RER U	599	510	2,669	3,555	4%	1
	Polyethylene, HDPE, granulate, at plant/RER U	1 508	1 288	6 440	9 002	3%	1
	Polyethylene, LDPE, granulate, at plant/RER U	318	265	1 600	4 434	3%	1
Paint	Alkyd paint, white, 60% in H_2O, at plant/RER U	2 798	2 517	17 231	54 893	7%	2
Glass	Flat glass, coated, at plant/RER U	167	122	799	2 074	5%	2
	Flat glass, uncoated, at plant/RER U	167	122	799	2 074	5%	2
Wood	Plywood, outdoor use, at plant/RER U	209	153	998	2 593	4%	2
	Glued laminated timber, outdoor use, at plant/RER U	42	42	166	166	4%	2
	Glued laminated timber, indoor use, at plant/RER U	444	348	1 711	5 766	4%	1
Brick	Brick, at plant/RER U	73 780	66 892	286 365	997 445	4%	1
Ceramic	Ceramic tiles, at regional storage/CH U	6 354	5 320	45 892	117 617	5%	1
	Roof tiles, at plant/CH U	5 884	4 978	29 145	38 817	5%	2
Stone	Limestone, milled, packed, at plant/CH U	436	430	1 572	2 745	5%	1

Plant material	Database entry	Amount (kg)				WF (%)	LS (-)
		SFH	TH	MFB	AB		
Aluminum	Aluminum, production mix, at plant/RER U	140	140	1 180	2 620	5%	3
Plastic	Polyethylene, HDPE, granulate, at plant/RER U	73	65	304	830	10%	1
Copper	Copper, at regional storage/RER U	73	57	199	573	7%	1
Brass	Brass, at plant/CH U	26	26	120	168	N/A	1
Ceramic	Sanitary ceramics, at regional storage/CH U	398	398	1 998	4 676	N/A	1

Table A.2. Different cost categories for SFH, TH, MFB, AB, equipped with Building systems 3, in Turin

Cost categories	Cost (€)			
	SFH	TH	MFB	AB
Investment costs:				
Building components	160 227	134 220	802 960	1 847 061
Building systems	38 378	34 951	207 208	508 410
Replacement costs:				
Lifespan 15 years	8 213	8 213	49 281	114 988
Lifespan 20 years	3 659	3 659	9 478	25 091
Lifespan 25 years	6 436	4 347	19 648	78 548
Lifespan 30 years	19 995	19 110	125 310	198 582
Lifespan 40 years	3 659	3 659	9 478	25 091
Final value at the end of the calculation period	16 710	13 678	76 256	148 895
Annual running costs	1 008	900	17 211	46 854
Annual energy costs:				
Gas	750	538	2 815	7 628
Electricity	722	571	3 307	11 718
Water	130	110	785	2 245

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