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Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock

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ABSTRACT

This study describes the results of Life Cycle Assessment (LCA) applied to 24 statistically-based dwelling archetypes, representative of the EU housing stock in 2010. The aim is to quantify the average environmental impacts related to housing in Europe and to define reference values (baseline scenario) for policies development. The average environmental impacts have been calculated taking into consideration the number of dwellings (clustered per typology, year of construction and climate zone) related to each representative model. System boundaries include production, construction, use (energy and water consumption), maintenance/replacement, and end-of-life phases of each dwelling. The environmental life cycle impact assessment was carried out using the ILCD method. EU average annual environmental impact per person, per dwelling, and per m^2 were calculated. Results show that the average life cycle greenhouse gases emissions related to housing per person per year are 2.62 t CO_2eq and related to a representative dwelling per year are of 6.36 t CO_2eq. The use phase (energy and water consumption) is the most relevant one, followed by the production and the maintenance/replacement phases. Single-family houses are responsible for the highest share of impacts related to housing in Europe. The same type of building has different impacts in different climatic zones, due to the differences in the need for space heating. In general, electricity use and space heating are the activities that contribute more to the overall impacts. The final results could be used as a baseline scenario for testing eco-innovation scenarios and setting targets toward impact reduction.

1. Introduction

The built environment is one of the main drivers of environmental impacts in Europe and represents one of the most important areas of intervention for reducing emissions and consumptions of resources.

In recent years, several European policy initiatives, such as the Europe 2020 Strategy and the Resource-efficient Europe flagship [1], identified the built environment as one of the strategic areas. As a result, there are many guidelines and European directives on the construction sector, in particular those related to the reduction of energy consumption in the use phase of buildings (which contributed to 41% of EU energy consumption in 2010). These directives aim to reduce the overall environmental impacts of buildings. However, the main policies tend to focus only on the most impacting phase (use phase) and on the most known drivers of impacts (such as energy and CO_2 emissions) without checking the effects of the promoted strategies on the entire life cycle of the impacts and considering a variety of environmental impacts. The risk, in fact, is to create burden shifting among the life cycle phases and among the different impacts.

During the years, several requirements were defined to improve the energy performance of buildings (e.g. increase of thermal resistance), through the 2002 and 2010 Energy Performance of Buildings Directive (EPBD) [2–4] and the 2012 Energy Efficiency Directive [5]. Nonetheless improving the energy performance of buildings toward Zero Energy Buildings, the impacts derived from the production of building materials and equipment can overcome the impacts related to the use phase. It should be emphasized that not all the energy efficiency strategies, including the regulatory ones, lead to an overall reduction of the environmental impacts. In fact, while in old buildings the ratio of impacts between the production of materials and the impact of energy consumption on the use phase is 1:10, in low-energy buildings the embodied energy can represent the 45% of the lifecycle energy [6,7].

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Some studies highlight that, adopting a life cycle approach, the impacts of the production, maintenance, and end-of-life phases can be higher than the impacts of the use phase in low-energy buildings and zero-energy buildings [8–14], even in the case of refurbishment [15,16]. Moreover, assessing only energy or CO_2 emissions is very restrictive, since buildings are responsible also of other resource consumption (such as land, water, minerals and metals) and of other emissions (causing for example acidification, eutrophication, and ecotoxicity).

The European Directives often deal separately with environmental issues, without verifying any burden shifting between types of environmental impact. For example, waste issue is also considered important, but it is regulated by another directive, with objectives completely uncorrelated from those of energy efficiency. Construction and Demolition Waste (CDW) is one of the heaviest and most voluminous waste generated in the EU, accounting for approximately 25–30% of total EU waste. The Waste Framework Directive [17] stipulates that Member States have to take the necessary measures to achieve within 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste for re-use, recycling or other material recovery. But even in this case, life cycle was not considered: the huge amount of inert materials, for instance, easily achieves the target of 70% prepared to recycling (potential), but downcycling is typically applied [18], or materials are stocked for long time. Furthermore, the avoided impacts derived from the recycling of inert material are low (excluding land use and resources consumption) and the recycling process can have higher impacts than the extraction of virgin materials, since recycled aggregates must be processed while natural aggregates are available in nature.

Rules related to ecoefficiency are growing in the building sector, both for the introduction of regulatory restrictions (e.g. Directives, Green Public Procurement) and for the introduction of voluntary incentive tools, like Green Building Rating Systems (e.g. LEED, BREEAM, Level). Nevertheless, these rules are often not verified in their effects on the total impacts. Requirements deal separately with the environmental aspects (energy, waste, resources), without a unified vision and without a verification of the effects of requirements on the overall impacts and on the entire life cycle.

In July 2014, the European Commission adopted the Communication on Resource Efficiency Opportunities in the Building Sector [19]. This Communication identified the need for a common European approach to assess the environmental performance of buildings throughout their lifecycle, taking into account the use of resources such as energy, materials and water. A study to develop a common EU framework of indicators for the assessment of the environmental performance of buildings was undertaken during 2015–2017 by the Environment and Growth Directorates-General of the European Commission (DG ENV and DG GROW), with the technical support of the European Commission's Joint Research Centre [20,21].

In this framework, Life cycle assessment (LCA) plays a strategic role in identifying critical aspects and potential impacts of the current situation and in supporting the identification of actions, policies and strategies that can help to reduce environmental impacts, verifying their environmental effectiveness and considering the entire life cycle and several environmental impact categories.

With the aim of managing transformations of built environment toward sustainability, the building stock should be seen as a supply of resources (urban mining and buildings as material banks) to be conserved and reinvented with a new value. This means monitoring the building stock in order to understand which are the critical issues that generate the highest impacts and to overcome those issues with specific interventions. The efficacy of the interventions may be tested by building scenarios to be compared with a baseline, hence, supporting policies and legislation.

Although a great number of ‘bottom-up’ product-oriented LCAs of residential buildings have been carried out [6,22–26]. However, it is difficult to compare the results of these studies because they are related to specific buildings in specific conditions. The potential impact of the eco-innovations and eco-solutions proposed in these studies remains uncertain, if applied at the European scale. Evidently, we cannot assume that the results are the same in every climatic condition or for any type of building (e.g. with different ages of construction or technical features).

A representative model of the existing building stock in Europe is needed to assess this kind of scenarios, as done in some EU projects for simulating the effects of energy efficiency measures and defining target values for policy and regulatory implementation (e.g. energy consumption limits according to the EPBD). Within the two projects TABULA (“Typology Approach for Building Stock Energy Assessment”) [27] and ENTRANZE (“Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks”) [28], funded by the European programme Intelligent Energy Europe (IEE), an effort was done to create reference data for “European building typologies”. The abovementioned projects aim to analyze the energy consumption of the residential building stock in EU and the potential impact of its energy optimisation. However, the LCA approach was not included in these studies.

As a consequence, until now, there was a lack of reference values, representative of the average environmental performance, to be compared with the results of individual LCA studies of buildings.

Some authors have developed benchmarks, but they are context-specific [29] or they identify targets for new buildings [30], defining an average value related to representative buildings compliant with current regulations. Hence, benchmarks on the current environmental impact of the existing European residential building stock are still missing.

Therefore, the environmental assessment of representative dwellings (defined with the support of statistical and EU project data) represents the main novelty of the present work that, applying the LCA methodology, aims thus to evaluate the impacts of the whole European building stock to support policy scenarios.

2. Objectives and methodology of the research

This paper reports the results of a research that applies Life Cycle Assessment (LCA) method to quantify the average environmental impacts associated with the current European residential building stock (which constitutes 60% of Europe's overall building stock).

For this purpose, it was applied the methodology developed by JRC starting from 2010. Indeed, with the aim to comprehensively assess the life cycle impact of final consumptions at European level, the European Commission's Joint Research Centre (JRC) has worked up a lifecycle-based methodology focusing on specific representative products, which are then upscaled to the overall EU consumption. The project entitled “Life cycle indicators for resources, products and waste. Basket-of-products” [31–33] was designed to establish the average environmental impact of a European citizen in relation to three main consumption categories: food [34], mobility, and housing. In order to define a baseline scenario, statistical data were gathered for each sector and a ‘basket’ of representative products (Basket of Products – BoP) was chosen to perform LCA analysis, establishing the average impact associated with them. A top-down approach based on statistical data was thus combined with a bottom-up approach based on the LCA of individual ‘products’. The ultimate goal was to establish benchmark values for the current situation and targets for improvement.

New development was defined in the context of the project “Indicators and assessment of the environmental impact of EU consumption (LC-IND2)”, funded by the Directorate-General for the Environment (DG ENV).

In this context, the paper presents the preliminary research to calculate the baseline scenario for the housing consumption category, “Basket of Products: housing”, embedded in the report “Indicators and targets for the reduction of the environmental impact of EU consumption" [35]. In 2017, the JRC published the complete results, including an evaluation of a number of eco-innovation scenarios [36].

The preliminary research to calculate the baseline scenario (concerning EU-27 for the reference year 2010) was conducted with the following steps:

- analysis of the features of the current European housing stock, gathering statistical data about size, type, period of construction, technical characteristics and energy consumption;
- cluster-based subdivision of the European residential building stock (according to type, climate zone, period of construction), establishment of representative models (dwellings) for each cluster and detailed identification of the typological and construction characteristics for each representative building, based on statistical data and scientific literature;
- development of process-based LCI models for the selected representative dwellings and for each phase of their life;
- calculation of the environmental impacts from cradle to grave of the different representative dwellings using the LCA method and scaling up the results in order to assess the overall European environmental impacts;
- establishment of a baseline scenario, reporting LCA benchmark values, in relation to the average annual environmental impact of a European dwelling (these data are also expressed in terms of average annual impacts of a European citizen and of one square metre of living space);
- identification of critical aspects and priorities for action.

In the following sections, each methodological step is described in detail.

3. Development of representative models based on statistical data

In order to develop representative models, it was necessary to define archetypes of dwellings, by dividing the current building stock into clusters. In the building sector there is no standard way to cluster buildings by types and there are also different interpretations of the categories used in statistics. In BoP-housing, the main features selected to cluster the building stock and define the 'product groups' (or clusters) are: dwelling typology, period of construction and climate zone in which the building is located. This choice was dictate by the availability of statistical data regarding the amount of dwellings in relation to each cluster of the breakdown applied.

Based on the availability of statistical data, two typologies of dwelling were identified: Single-Family House (SFH) and apartments in Multi-Family House (MFH). The representative 'product' for each 'product group' was chosen according to its diffusion:

- the dwelling in a Detached House (Fig. S1) was selected as representative 'product' for the "dwelling in SFH" product group, since 34.4% of EU-27 population live in detached houses (Eurostat, 2014a);
- the apartment in a low-rise MFH with more than 10 dwellings (Fig. S1) was selected as representative 'product' for the "dwelling in MFH" product group (this type of building is widespread especially in urban areas, considering aged buildings, even if its amount is not supported by statistical data).

With regard to climate zones, Europe has been divided into three areas. Each country has been related to a climatic zone according to the national average Heating Degree Days (HDD):

- climatic zone 1, warm climate with 500–2300 HDD (Malta, Cyprus, Portugal, Greece, Spain, Italy);
- climatic zone 2, moderate climate with 2301-4000 HDD (France, Slovenia, Hungary, Romania, Bulgaria, Ireland, Netherlands, Belgium, Luxembourg, United Kingdom, Slovakia, Germany, Austria, Czech Republic, Poland, Denmark);
- climatic zone 3, cold climate with 4001–6000 HDD (Lithuania, Latvia, Estonia, Sweden, Finland).

The subdivision into three climatic zones was already adopted by other studies [37,38] and reflects the changes in the number of HDD in relation to latitude (35°–45°; 45°–55° and 55°–70°), even if not fully representing the climatic differences of each climatic zone (influenced by regional macroclimate, local microclimate and the related altitude). However, the national average HDD points out the variation existing in climate at different latitudes, which affects the average heating energy consumption of buildings in the different countries. Nonetheless, in this study the energy consumption of the use phase was not calculated based on the national average HDD but according to the energy consumption (for each Member State) taken from statistical data.

Concerning the period of construction, starting from the availability of statistical data and the introduction of technical and legislative innovations (e.g. the transition from single to double glazing, thickness of insulation material, transition from radiators to underfloor heating systems, etc.), four periods were identified (Table S1): pre-1945, 1945–1969, 1970–1989, and 1990–2008.

By combining these categories, 24 clusters of dwellings were defined, breaking down the total European dwelling (Table S2), and for each of them a representative model was built up [39] with the relative different features.

3.1. Data sources used for building the representative models

To define the representative dwellings of the BoP-housing, a detailed analysis was performed by consulting various statistical data sources of the European housing stock [39]. The study focused on the analysis of the stock of permanently occupied dwellings, since the only one supported by statistical data.

A first screening of statistical data was conducted using the Eurostat database [40]. In addition, the research projects developed by Intelligent Energy Europe (IEE), such as TABULA [27], ENTRANZE [28], ODYSSEE [41] and EPISCOPE [42], were particularly useful for the detailed information included. These sources, based on the collection of national statistical data, provide information on the magnitude of the building stock, the periods of construction, the physical characteristics, and the energy consumption. For the present study, the most useful source was the Data Hub elaborated by the Buildings Performance Institute Europe (BPIE[1]) [43]. It should be noted that the different data sources adopted are heterogeneous.[2] Very few reports cover all information needed, so different sources have been combined, adopting the most common ones, the closest to the objectives of the study and more transparent (with a greater description of what the data represents).

In some cases, it was not possible to find data related to Member States of EU-27 and to the reference year 2010 (scope of the study). Nevertheless, it should be noted that the average values of statistical data (e.g. square metres of a dwelling) barely change from year to year, and among countries. Hence, when there were no data available for EU-27 in 2010, data related to whole Europe and the year 2008 have been used.

Statistical data are available for: number of dwellings per each

[1] BPIE is a not-for-profit think tank that supports several IEE and FP7 European Projects. BPIE collects data about the quantity and quality of the building stock and the energy performance of buildings, from national statistics and studies.

[2] The analysis of the available statistical data discovered different ways of aggregating data from country to country. This is partly explained by different building classification rules.

cluster (Table S1); average floor area (m^2) per dwelling by dwelling type, by Member State and by period of construction (Table S10); average number of inhabitants per dwelling by dwelling type and by climatic zone (Table S7); U-value; average energy consumption per dwelling by climatic zone (Table S5b) and per person (Tables S6a–S6e).

Each dwelling type is also characterised by other building features, such as the number of dwellings for building type, the number of floors, the internal height, the window-to-wall ratio, the construction technologies and the expected lifespan of the building. Assumptions based on scientific literature have been made for these parameters for defining the representative 'product' to be included in the basket (as detailed in section 4).

The key features assumed for each of the twenty-four models are: floor area of dwelling, number of occupants, inter-floor height, basement floor area, heated volume, surface-to-volume ratio, window-to-wall ratio (envelope), construction technology (foundations, load-bearing structure, floors, staircases, building envelopes, finishing, windows, roof, lower floor, internal partitions), thermal transmittance values (building envelope, roof, lower floor, windows and doors), heating energy consumption, heating system (generator and terminals). The key features are shown in Table 1 (for Single-Family House) and Table 2 (for Multi-Family House).

4. Key assumptions for the LCA of representative models

LCA was conducted in compliance with the standard EN 15978:2011 [44], encompassing a cradle-to-grave approach as system boundaries. Inventory data and results were organized with a modular structure into the following life cycle phases: production, construction (transport, energy and waste), use (energy and water), use (maintenance/replacement) and End of Life (EoL). For each lifecycle stage, process-based LCIs were developed for each representative dwelling (Table S3). Unlike the standard EN 15978, the benefits of recycling and energy recovery of EoL have been considered, for consistency with the assumption of the baskets on food, household goods, household appliances, and mobility. Furthermore, the Life Cycle Impact Assessment (LCIA) methodology follows ILCD (International Reference Life Cycle Data System) recommendations at midpoint [45], version ILCD 1.08: in this way the impact categories considered are not the typical of EN 15978 standard. Long-term emissions have been excluded. A sensitivity analysis was carried out with the aim to find out which impact category is more affected by the exclusion of long-term emissions (Table S9).

The results have been related for three functional unit:

- the average impacts related to housing for an average EU-27 citizen during one year (considering 2010 as reference year);
- the average impacts related to an average EU-27 dwelling during one year;
- the average impacts related to one square meter of an average EU-27 dwelling during one year.

For the development of LCI datasets (which refers to the 24 representative models) and LCA analysis, SimaPro 8.3 software and Ecoinvent 3.2 database were used. The curtilage (the land immediately surrounding the dwelling) was omitted. No cut-off was considered.

The total lifetime of the buildings was assumed to be 100 years (considering that a relevant share of the building stock was constructed before 1945, i.e. more than 70 years ago). Despite in literature the lifespan of buildings ranges from 50 [6] to 100 years [46,47], buildings often last centuries, according to Méquignon and Hassan [48], especially with regards to their structures.

4.1. Assumptions for the production phase

For the production phase, all materials used in the building were taken into consideration, including sanitary fixtures as well as heating/cooling, electrical, and plumbing systems.

With regard to building technology, typical construction systems were selected considering the period of construction of the building and the different climate zone. The same technological solutions were assumed both for the period 1945–1969 and the period before 1945, under the assumption that the changes occurred in building materials and components were negligible.[3] All the technical solutions of the envelope (walls, windows, roofs, etc.) of the representative buildings were modelled (size and choice of materials) taking into account the statistical thermal transmittance (U-value) and combining data from TABULA Project [27,49] and BPIE[4] [43] as well as expert judgments on the characteristics of the regional construction materials. Massive building envelope system is assumed to be representative of all EU-27 dwellings in warm and moderate climates. For cold climates, massive building envelope system is assumed only for MFH, whereas wood lightweight construction system is assumed to be representative of the SFH building type. The insulation material chosen for all of the representative dwellings is rock wool, which (together with glass wool) accounts for 60% of the market of insulating materials; while organic foamy materials, expanded and extruded polystyrene and polyurethane account only for 27% of the market [50].

With regard to the heating system, it has been assumed that radiators were used up to 1990 in warm and moderate climates and that the transition from radiators to radiant floors was made after 1990.[5] Between 1945 and 1970, the amount of steel pipes in the heating system increased due to the displacement of radiators from the hallway proximity (to reduce pipes' length) to the below-window location (designed to improve heat distribution and comfort). Since electricity is the typical fuel used for heating systems in cold climates, convector heaters were chosen as the most representative solutions for this category.

The system boundaries of material production include the extraction of raw materials or recovery of recycled materials (as available in Ecoinvent 3.2 datasets, referring to the EU-27 average when possible), the transport to the manufacturing plant and the production processes. The building elements included in the inventory are: supporting structure (foundations, underground retaining walls, load-bearing elements, floors, stairs), envelope (external walls, windows, roof, lower floor), internal walls, finishes, systems (heating, wiring, plumbing, sanitary appliances).

4.2. Assumptions for the construction phase

For the construction phase, the impacts of transport, assembly and production of construction waste were calculated, also taking into account the impacts of the re-production of materials that turn into waste. The impact of transport from manufacturing plant to building site was calculated on an average distance of 50 km [51] for massive materials and 100 km [52] for other materials. As stated in literature [51,53,54], the impact of the assembly phase in terms of electrical consumption is assumed to be equal to 2% of the embodied energy of all the building materials. It is assumed that 4% of the construction materials are wasted on the construction site (this quantity has been considered as

[3] This assumption is compelling for the building stock of 1900–1945, whereas expired for the period before 1900 since in this case the stock is too heterogeneous and it includes historical buildings.

[4] The construction solutions (which materials, which "layers") have been defined using TABULA case studies as reference. Then the solutions have been modified (in thickness of the insulation layer) according to BPIE data related to average statistical U-value for each cluster.

[5] The assumption that radiant floors are used starting from 1990 in warm and moderate climates derives from interview with experts. It must be considered that before this period it is not possible to consider a spread of the radiant floors extended to all new buildings, and therefore assumed as reference technology; there are some applications before 1990, but they concern a reduced percentage of buildings.

Table 1
Main features of the representative dwellings chosen for the Single Family House group.

Dwelling type	Single Family House											
	SFH_warm_ < 1945	SFH_war-m_1945-69	SFH_war-m_1970-89	SFH_war-m_1990–2010	SFH_moderat-e_ < 1945	SFH_moderat-e_1945-69	SFH_moderat-e_1970-89	SFH_moderat-e_1990–2010	SFH_cold_ < 1945	SFH_col-d_1945-69	SFH_col-d_1970-89	SFH_col-d_1990–2010
Building typology	Detached House											
Number of dwelling	1											
Number of floors	2											
Lifetime of the building	100 years											
Climate	warm				moderate				cold			
HeatingDegreeDays	500–2300				2301–4000				4001–6000			
Year of construction	1945–1969	1945–1969	1970–1989	1990–2010	1945–1969	1945–1969	1970–1989	1990–2010	1945–1969	1945–1969	1970–1989	1990–2010
Model dwelling size (m^2)	100			130	90		100		100		120	
Number of inhabitants	3.43				2.71				2.83			
Internal height (m)	2.7				2.5				2.5			
Surface/Volume	0.92			0.85	0.98			0.95	0.92		0.87	
Window-to-wall ratio	0.29			0.31	0.30		0.32	0.32	0.30		0.28	
Constructive technology	heavy				heavy				light, dry assembly			
Foundations	reinforced concrete curb											
Underground retaining walls	reinforced concrete											
Load bearing elements	masonry in brick				masonry in brick				timber frame			
Floors (structure)	reinforced concrete/bricks				reinforced concrete				timber frame + board			
Stairs	reinforced concrete				reinforced concrete				timber frame			
External walls	masonry brick (25 cm)			masonry brick (25 cm)	masonry brick (32 cm)	masonry brick (38 cm)	masonry brick (30 cm)	masonry brick (32 cm)	timber frame		timber frame	timber frame
Insulation	no insulation			insulation (2 cm)	no insulation	no insulation	no insulation	insulation (5 cm)	insulation (4 cm)		insulation (5 cm)	insulation (6 cm)
External walls finishes	plaster				plaster				wood			
Windows	wood frame single glass				wood frame single glass			PVC frame double glass	wood frame single glass		wood frame double glass	wood frame triple glass
Roof Insulation	pitched no insulation			flat insulation (2 cm)	pitched insulation (2 cm)		pitched insulation (5 cm)	pitched insulation (10 cm)	pitched insulation (4 cm)			pitched insulation (7 cm)
Bottom floor	no insulation		insulation (1 cm)	insulation (1 cm)	insulation (1 cm)		insulation (2 cm)	insulation (8 cm)	insulation (7 cm)		insulation (8 cm)	insulation (11 cm)
Roof finishes	brick tiles				brick tiles				cement tiles			
Internal walls	hollow brciks				wood frame				wood frame			
Internal walls finishes	plaster				plasterboard				plasterboard			
Flooring	ceramic tiles				ceramic tiles				wood			
U-value walls	1.71		1.47	0.82	1.54		0.98	0.5	0.64		0.52	0.39
U-value roof	2.32		2.19	1.18	1.38		0.72	0.35	0.75		0.71	0.47
U-value windows	4.00		3.45	3.00	3.65		2.65	1.84	2.30		2.01	1.87
U-value bottom floor	1.76		1.71	1.48	1.63		1.16	0.49	0.49		0.43	0.33
Heating energy consumption	108	102	76	62	220	184	151	100	190	175	150	115
Heating systems	boiler				boiler				electricity			
Heating terminal unit	radiators			radiant floor	radiators			radiant floor	convector heaters			
Tot nr. of dwellings in EU-27	3,990,078	3,940,268	5,029,842	3,015,954	19,053,376	21,741,474	24,874,549	15,835,402	1,137,005	1,123,212	1,258,137	629,666
Tot nr. of people living in the dwelling EU-27	54,801,521				221,050,717				11,733,022			

Table 2
Main features of the representative dwellings chosen for the Multi-Family House group.

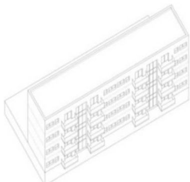
Dwelling Type 	Multi-Family House											
	MFH_warm_- < 1945	MFH_war-m_1945-69	MFH_war-m_1970-89	MFH_war-m_1990–2010	MFH_modera-te_ < 1945	MFH_modera-te_1945-69	MFH_modera-te_1970-89	MFH_moderate_1990–2010	MFH_cold_ < 1945	MFH_col-d_1945-69	MFH_col-d_1970-89	MFH_col-d_1990–2010
Building typology	Low-rise > 10 apartment											
Number of dwelling	16											
Number of floors	4											
Lifetime of the building	100 years											
Climate	warm				moderate				cold			
HeatingDegreeDays	500–2300				2301–4000				4001–6000			
Year of construction	1945–1969	1945–1969	1970–1989	1990–2010	1945–1969	1945–1969	1970–1989	1990–2010	1945–1969	1945–1969	1970–1989	1990–2010
Model dwelling size (m^2)	90				60				60			
Number of inhabitants	2.03				2.05				1.67			
Internal height (m)	2.7				2.5				2.5			
Surface/Volume	0.55				0.65				0.65			
Window-to-wall ratio	0.22				0.26				0.26			
Constructive technology	heavy				heavy				light, dry assembly			
Foundations	reinforced concrete curb											
Underground retaining walls	reinforced concrete											
Load bearing elements	reinforced concrete frame											
Floors (structure)	reinforced concrete/bricks				reinforced concrete				reinforced concrete			
Stairs	reinforced concrete											
External walls	hollow bricks (30 cm)			hollow bricks (30 cm)	hollow bricks (30 cm)		hollow bricks (20 cm)		hollow bricks 8 cm			
Insulation	no insulation			insulation (2 cm)	no insulation		insulation (2 cm)	insulation (4 cm)	insulation (3 cm)			
External walls finishes	plaster				plaster				facing bricks (12 cm)			
Windows	wood frame single glass		aluminium frame double glass		wood frame double glass		PVC frame double glass		wood frame single glass		wood frame double glass	alum frame double glass
Roof	flat			flat	flat		flat	flat	pitched		pitched	pitched
Insulation	no insulation			insulation (2 cm)	insulation (2 cm)		insulation (4 cm)	insulation (10 cm)	insulation (4 cm)		insulation (5 cm)	insulation (8 cm)
Bottom floor	no insulation	no insulation	insulation (1 cm)		insulation (1 cm)		insulation (2 cm)	insulation (7 cm)	insulation (5 cm)		insulation (6 cm)	insulation (9 cm)
Roof finishes	bitumen				bitumen				cement tiles			
Internal walls	bricks				wood frame				wood frame			
Internal walls finishes	plaster				plasterboard				plasterboard			
Flooring	ceramic tiles				ceramic tile				wood			
Uvalue walls	1.76		1.47	0.81	1.55		0.98	0.54	0.71		0.54	0.58
Uvalue roof	2.25		2.11	1.16	1.42		0.75	0.39	0.79		0.73	0.48
Uvalue windows	4.80		4.90	3.75	3.81		2.90	1.93	2.20		2.04	1.97
Uvalue bottom floor	1.81		1.73	1.52	1.67		1.16	0.51	0.57		0.51	0.38
Heating energy consumption	101	98	63	52	182		133	98	158	168	148	129
Heating systems	boiler				boiler				electricity			
Heating terminal unit	radiators			radiant floor	radiators			radiant floor	convector heaters			
Tot nr. of dwellings in EU-27	5,563,385	10,977,814	12,326,198	6,923,950	12,883,862	16,543,072	19,849,947	11,961,082	1,326,949	1,580,981	1,831,829	910,548
Tot nr. of people living in the dwelling EU-27	72,640,110				125,289,263				9,463,779			

Table 3
Total annual (related to 2010) EU-27 LCA impacts in relation to housing.

Impact category	Unit	Housing
Climate change	kg CO_2 eq	1.24E+12
Ozone depletion	kg CFC-11 eq	1.57E+05
Human toxicity, non-cancer effects	CTUh	1.29E+05
Human toxicity, cancer effects	CTUh	1.68E+04
Particulate matter	kg $PM_{2.5}$ eq	1.39E+09
Ionizing radiation, effects on human health (HH)	kBq U^{235} eq	9.71E+10
Photochemical ozone formation	kg NMVOC eq	2.91E+09
Acidification	molc H^+ eq	6.37E+09
Terrestrial eutrophication	molc N eq	8.79E+09
Freshwater eutrophication	kg P eq	7.04E+07
Marine eutrophication	kg N eq	8.00E+08
Freshwater ecotoxicity	CTUe	5.46E+11
Land use	kg C deficit	2.31E+12
Water resource depletion	m^3 water eq	7.18E+10
Resource depletion	kg Sb eq	5.69E+07

construction waste and as an additional amount of materials to be produced).

4.3. Assumptions for the use phase (energy and water)

For the use phase, energy consumption (heating, domestic hot water, cooling, cooking, lighting and electrical appliances) and water consumption were considered. Statistical data were taken and then reworked in order to establish specific consumption values for the different models. This means that the amount of energy used for housing in EU-27 for each of the abovementioned activities was allocated to the 24 representative dwellings defined in the model of the EU-27 building stock.

The main reason for choosing a top-down approach for modelling energy use in the use phase, rather than calculating the energy consumption for each representative dwelling starting from its characteristics and by means of energy simulation tools, is that the scope of the work is the entire housing sector in EU and not the single buildings. Therefore, in line with the scope, it was considered more relevant to ensure consistency of the total amount of energy used in EU-27 rather than the amount of energy used in each representative dwelling. The average energy consumption was derived from EU-27 energy statistics. In particular, the average heating consumption for each representative dwelling was calculated by merging the annual statistical data gathered from BPIE about the heating consumption of a dwelling type, by period of construction and by Member State (Table S4) with the total heating consumption given by Member State and gathered from ODYSSEE (Table S5a, S5b, S5c).[6] For the other energy consumption contributions, i.e. water heating, space cooling, cooking, lighting and appliances, a European average value per person for each energy consumption type was considered (Tables S6a, S6b, S6c, S6d, S6e), starting from the statistical data related to the total energy consumption of each climate zone found in ODYSSEE and dividing for the number of person of each climate zone. Then the value related to the consumption of a person for each type of consumption and for each climatic zone has been multiplied by the average number of people assigned to each representative model. The average number of inhabitants by representative model was calculated from statistical data (Table S7). To define the environmental impacts related to the energy consumption, it was also necessary to know which energy source is used in each country (Table S8). Energy consumptions were then associated with the related energy carriers (natural gas, diesel, wood, waste-to-energy, coal and electricity), based on statistical data [41], in order to assign the respective environmental impact. The European electricity mix was used.

With regard to water consumption, an European average value of 150 L per person per day [55,56] was assumed. The same amount is supposed to be treated after use. The treatment has been modelled as conventional treatment of wastewater from residential uses in an average European urban wastewater treatment plant (three-stage wastewater treatment - mechanical, biological, chemical - including sludge digestion). Finally, the solid wastes in the use phase were disregarded since they are not building-related.

4.4. Assumptions for the replacement phase

For the replacement during the building's use phase, the system boundary includes the production of the components to be replaced, their transportation (50 km) and the end-of-life of the removed components (burdens and benefits from recycling and energy recovery). Data on average replacement periods were found in literature [57,58]: 30 years for mineral insulation, 30 years for windows, 50 years for external walls in wood frame (light construction), 30 years for internal walls in wood frame (light construction), 20 years for waterproofing, 50 years for finishes (replacement of 50% of the finishes every 25 years), 50 years for the systems (replacement of 50% of systems every 25 years). These values were applied both to new buildings (as future scenario along the service life) and to the old stock (assuming that replacements occurred starting from its construction).

4.5. Assumptions for the end of life phase

Finally, for the end-of-life phase, the impacts of the building demolition process (energy end emissions for dismantling), the transportation to the waste treatment centre (50 km), the treatment at the sorting plant (machines for handling, electricity demand, emissions from handling) and any impacts of landfill disposal (residual inert masses) were considered, as well as impacts and benefits associated with recycling operations. After treatment, the sorted materials can be landfilled, incinerated or recycled. Both benefits from recycling materials and energy recovery (incineration) were included in the system boundaries. It must be highlighted that a certain rate of uncertainty was introduced while defining the recyclability rate of the construction materials. Data on this topic are not always available, and the few available [59] are characterised by a certain rate of uncertainty depending on the data source (i.e. statistics at EU level, producer associations and case studies from literature).

5. LCA results

The overall results of the study represent the yearly potential impact of consumption in the EU-27 housing sector (Table 3). In order to calculate the total annual impacts of EU-27 in 2010, the overall impacts connected with the life cycle (production, construction, use, maintenance and end of life) of the various representative dwellings were divided by their useful life (assumed to be 100 years). The annual impacts of each type of dwelling were then multiplied by the total number of dwellings of the respective cluster.

An interesting aspect that emerges from both the analysis of statistical data and from the life-cycle assessments is the role of the unit of measurement used to explain the phenomena under investigation. For example, environmental impact data expressed per dwelling show that single-family buildings have a greater impact than multi-family buildings (Fig. S2). However, if the environmental impact data is expressed

[6] The definition of total consumption in kWh/m^2 per year by climate zone, type and period of construction has been defined using the following proportion. kWh consumption calculated from data reported in BPIE by climate zone, type and period of construction: total kWh consumption data BPIE = x (unknown): total real statistical consumption in kWh from ODYSSEE data (Table S5a). Results are in Table S5b. Then the total consumption was divided by the corresponding residential surface, to obtain the data in kWh/m^2 per year. These are the final data used in the assessment for heating consumption of each representative dwelling (Table S5c).

per square metre of floor area, the results changes totally, as single-family dwellings have a greater floor area, meaning that impacts per square metre are comparable to those of multi-family dwellings. In addition, considering the environmental impact expressed per inhabitant, single-family dwellings are similar to multi-family dwellings, since the average number of people that occupy single-family dwellings is higher than for dwellings in multi-family dwellings. For this reason, it is important to present results using different types of unit in order to avoid distorted interpretations.

To this end, the main results of the research are presented as:

- the annual environmental impact of the representative dwellings per person and per dwelling (section 5.1);
- the annual environmental impact of all the representative dwellings per person per life cycle stage (section 5.2);
- the annual environmental impact of the representative dwellings per square metre (section 5.3).

Moreover, results are displayed analysing the contribution of the different representative dwellings to the overall impacts (section 5.1).

It is important to underline that the definition of representative dwellings with average statistical values led to define buildings similar to each other, because they are defined on the basis of "average" and "common" characteristics. Indeed, average data are very "flat" and do not allow to highlight the differences between buildings. Being representative of the average data, there are small differences in the building stock: for example, the average square meters has small variation among the representative dwellings, but the actual minimum and maximum values range a lot. The same happens for the average energy consumption and other data.

In this way, representative dwellings fail to bear witness to the variety of typologies and technologies that are actually present in the entire building stock and hence do not represent the "minimum" and "maximum" environmental impact values present within the stock observed.[7]

5.1. Annual environmental impact of the representative dwellings per person and per dwelling in the EU-27 in 2010

To calculate the annual per-capita impacts of the average European citizen in relation to each representative dwelling, the overall life cycle impacts (production, construction, use, maintenance and end of life) of the various representative dwellings were divided by their useful life (assumed to be 100 years). The annual impacts of each type of dwelling were multiplied by the total number of dwellings in the respective cluster (Table S1) and divided by the total number of inhabitants per dwelling, by dwelling type and by climatic zone (Table S7) in order to obtain annualised impacts per capita by representative dwelling. Then the results were added each other, giving the annual per-capita impacts of the average European citizen.

Fig. 1 shows the relative importance of each "product group" on the overall impact of the BoP -housing for each impact category. The highest impacts are associated with the SFH in cold climate (Table 4), followed by the MFH in cold climate. The results are influenced by the occupancy factor: for example, in warm climates people who live in SFH have a lower impact than those who live in MFH due to the greater number of people per dwelling in SFH, which leads to a reduction in the overall impact per capita.

Finally, Table 5 shows the environmental impact associated with a single dwelling in each climatic zone, taking into account the number of dwellings and their impact (weighted average). It turns out that dwelling in SFH has a higher impact than dwelling in MFH for all the climate zones and all the impact categories.

5.2. Results per lifecycle stage per person per year in EU-27 in 2010

An analysis of the results was carried out to understand which stage of the lifecycle have the highest impacts. Table 6 and Fig. 2 show the average environmental impact of housing per citizen per year for EU-27 in 2010 and its distribution over the lifecycle stages within the system boundaries.

As stated in literature, the use phase (energy and water consumption) dominates the environmental impacts (from 56% to 97%, depending on the impact category; over 80% of impacts in 12 categories out of 15), as detailed below. The highest impact of the use phase is on Water resource depletion (97%); this is mainly due the electricity production (85%) and only around 6% is due to tap water consumption by users. The contribution to Ozone depletion (93%) is caused by electricity consumption in the use phase of buildings, but also by the use of light fuel oil and natural gas for heating and by incineration of municipal solid waste for district heating (due to refrigerant HCFC-22 and trichloromethane production for wastewater treatment). Ionizing radiation (94%) and Photochemical ozone formation (86%) are mainly due to electricity use. Freshwater eutrophication (92%) is also largely due to electricity use and, to a small extent, to wood heat and district heating (incineration of municipal solid waste). Acidification (88%), Photochemical ozone formation (86%), Climate change (91%) and Freshwater ecotoxicity (72%) are mainly due to electricity and secondarily to natural gas for heating. Land use (88%) and Human toxicity, non-cancer effects (84%) are mainly due to wood heating. Particulate matter (82%) and Terrestrial eutrophication (83%) are mainly due to fuels such as light fuel oil for heating and to electricity. Marine eutrophication (83%) is mainly due to electricity and, to a small extent, to the use of fuels other than natural gas, such as light fuel oil for heating. Human toxicity, cancer effects (56%) are mainly due to the electricity distribution network.

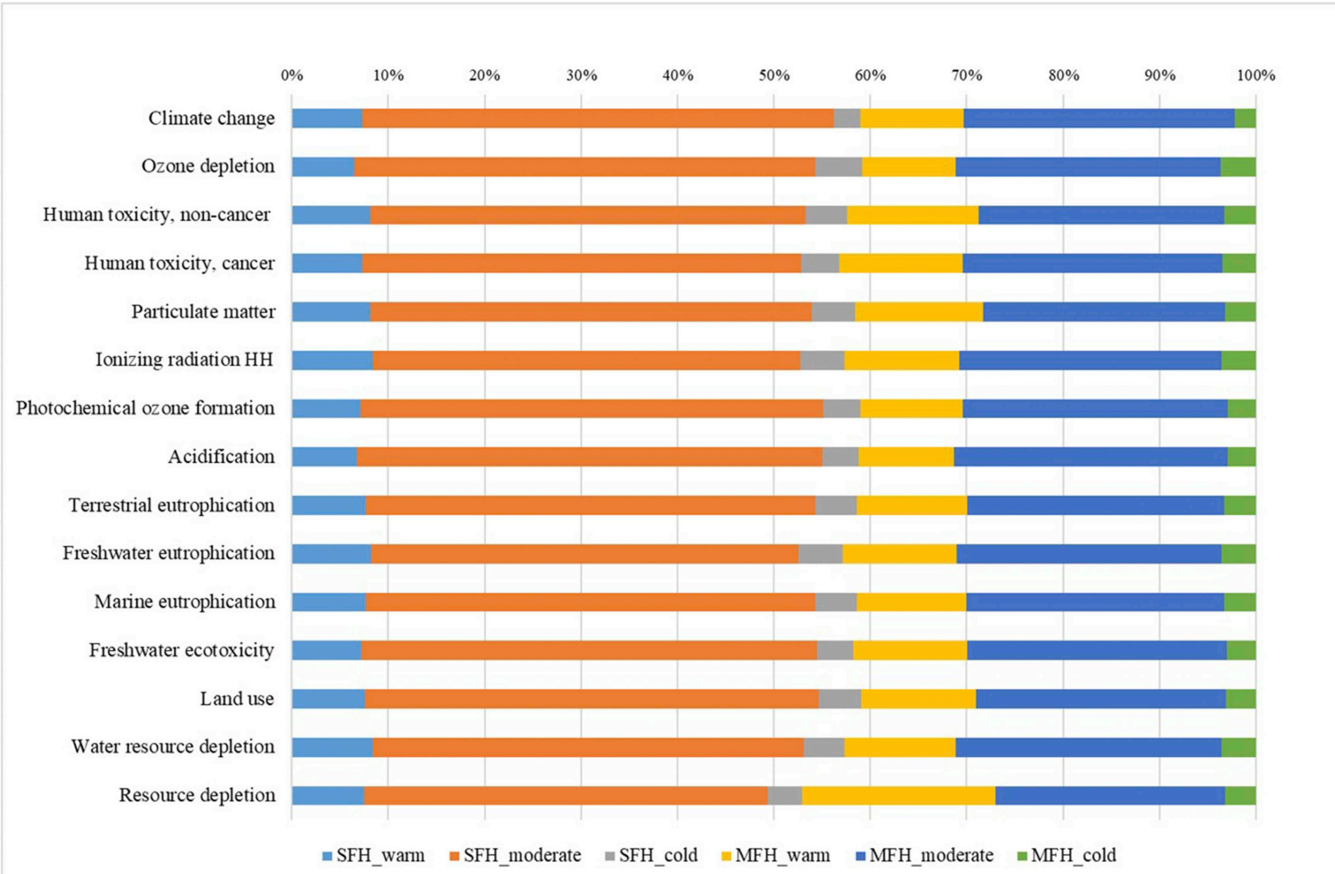
Given the relevance of the use phase in the overall impact, Fig. 3 shows the contribution of its sub-components to the overall impact of this lifecycle phase.

The production phase of building components also contributes significantly (from 3 to 40%, depending on the impact category), in particular with regard to steel (as concrete reinforcement), ceramic tiles, concrete and bricks production. The production phase dominates only in one indicator, namely Human toxicity, cancer effects (40%). This is due to the impact of reinforcing steel (90%) and specifically to metal emission from "Disposal to landfill of slag of unalloyed steel produced in electric furnaces", from "Basic oxygen furnace waste" and from "Sludge from steel rolling". The production phase importantly contributes to Freshwater ecotoxicity (19%) and Resource depletion (18%). The impact on Ecotoxicity is due to the production of reinforcing steel (77%), concrete, ceramic tiles and bricks. The impact on Resource depletion is mainly due to the production of ceramic tiles (57%), steel (28%), concrete and bricks. The production phase also contributes to Human toxicity, non-cancer effects (13%) due to the production of reinforcing steel and concrete.

In addition, also the maintenance phase has a non negligible impact (0.3–17.9%), mainly due to the consumption of resources. The maintenance/replacement phase significantly contributes in Resource depletion, mineral, fossil and renewables (17.9%), due to the production of finishes (ceramic tiles) and aluminium scrap prepared for melting aluminium during the recycling process. Particulate matter (4.2%) is mainly due to ceramic tiles (61%) and, to a small extent, to sanitary ceramics and waste gypsum plasterboard treatment. Acidification (3.9%) is mainly due to waste gypsum plasterboard treatment (42%); while Land use (3.3%) to the impact of wood components (for windows and internal walls).

The contribution of the construction phase never exceeds 4% in all

[7] It can be interesting observing the variation potential, but it is not useful to identify benchmarks and reference values, that is the goal of this study; so only average data have been considered.



Type	SFH_warm	SFH_moderate	SFH_cold	MFH_warm	MFH_moderate	MFH_cold
Share of typology of buildings over the total building stock	7.8 %	39.9 %	2 %	17.5 %	30 %	2.8 %
Occupancy factor	3.4	2.7	2.8	2	2	1.7

Fig. 1. Environmental impacts per capita associated to the different dwelling types and relative importance of the dwelling types over the entire building stock.

indicators. It should be highlighted that this result could be affected by the assumptions, i.e. oversimplification in setting the inventory of this phase (simply assuming a % of impact of the production phase), since it is not well documented in literature and detailed inventory data were not available.

Small burdens come also from end-of-life phase that slightly exceeds 4% in one impact category resource depletion) and from benefits for recycling phase that never exceed 1.9%.

In order to identify the most significant impact categories for the housing category, the results were normalized referring to the average impact per person in EU-27 [60–62] and applying equal weighting (Table S12). The normalisation step allows understanding the extent to which the environmental impacts of the housing sector in EU-27 contribute to the environmental impacts generated in EU-27 (taken as normalisation references). Normalized results (Table 7) may be aggregated in a single score applying weighting factors. An illustrative example of results, assuming equal weighting among impact categories, is reported in Fig. S3.

The four most significant impact categories are: Water consumption, Consumption of resources, Human toxicity, and Particulates. Water resource depletion (27.7%) appears as the most relevant impact category for the BoP-housing. This is mainly due to the use phase and in particular to the use of water for the production of electricity (59%). The value of water consumption in the inventory of the buildings includes the water depletion caused by cooling the power plants where electricity is produced (in background processes). If the contribution of cooling water (which is not true consumption, as it is used and discharged once again into the environment) is excluded, Water depletion contributes to only 3% of the overall impact of the BoP. The other important impact is the consumption of resources: Mineral, fossil & renewable resource depletion contributes 17.5% of the overall impact. The contribution analysis revealed the relevance of ceramic tiles for the production phase and of electricity for the use phase. The third most relevant impact category is Human toxicity, cancer effects, responsible for 14.1% of the overall impact and mainly due to the production of reinforcing steel. It is worthy to note that the contribution of toxicity-related impact categories should be further checked when improved impact assessment models for toxicity-related impacts would be available. In fact, there are some known issues related to the robustness of the impact assessment models for toxicity-related impacts. According to Zampori et al. [63], only 50% of the elementary flows contributing to toxicity are characterised by the impact assessment models currently available. EC-JRC is looking for the improvement of the issues; limitations of current model and the way forward are discussed in Saouter et al. [64,65]. Finally, also impact of Particulates, emitted during electricity production and the use of fuels for heating, are relevant.

Table 4
Average annual environmental impact of an EU citizen. Results per person are related to each representative dwelling. A colour code is applied from lower impact (in green), to higher impact (in orange).

Impact categories		SFH_warm	SFH_moderate	SFH_cold	MFH_warm	MFH_moderate	MFH_cold		Average SFH	Average MFH	EU housing average
Climate change	kg CO_2 eq	1.73E+03	2.87E+03	3.04E+03	1.93E+03	2.47E+03	2.97E+03		2.66E+03	2.30E+03	2.51E+03
Ozone depletion	kg CFC-11 eq	1.96E-04	3.56E-04	6.83E-04	2.19E-04	3.02E-04	6.35E-04		3.39E-04	2.88E-04	3.18E-04
Human toxicity, non-cancer effects	CTUh	1.98E-04	2.73E-04	4.92E-04	2.50E-04	2.36E-04	4.66E-04		2.68E-04	2.52E-04	2.61E-04
Human toxicity, cancer effects	CTUh	2.28E-05	3.54E-05	5.81E-05	3.04E-05	3.36E-05	6.34E-05		3.40E-05	3.39E-05	3.39E-05
Particulate matter	kg $PM_{2.5}$ eq	2.13E+00	2.97E+00	5.41E+00	2.63E+00	2.49E+00	4.89E+00		2.91E+00	2.65E+00	2.80E+00
Ionizing radiation HH	kBq U235 eq	1.55E+02	2.04E+02	4.00E+02	1.65E+02	1.85E+02	3.85E+02		2.02E+02	1.87E+02	1.96E+02
Photochemical ozone formation	kg NMVOC eq	3.95E+00	6.57E+00	9.81E+00	4.43E+00	5.71E+00	9.30E+00		6.20E+00	5.43E+00	5.88E+00
Acidification	molc H^+ eq	8.21E+00	1.45E+01	2.13E+01	9.03E+00	1.29E+01	2.03E+01		1.36E+01	1.19E+01	1.29E+01
Terrestrial eutrophication	molc N eq	1.28E+01	1.93E+01	3.35E+01	1.44E+01	1.67E+01	3.17E+01		1.86E+01	1.66E+01	1.78E+01
Freshwater eutrophication	kg P eq	1.10E-01	1.47E-01	2.87E-01	1.19E-01	1.37E-01	2.79E-01		1.46E-01	1.37E-01	1.42E-01
Marine eutrophication	kg N eq	1.16E+00	1.75E+00	3.08E+00	1.30E+00	1.52E+00	2.92E+00		1.69E+00	1.51E+00	1.62E+00
Freshwater ecotoxicity	CTUe	7.41E+02	1.21E+03	1.81E+03	9.23E+02	1.06E+03	1.82E+03		1.14E+03	1.05E+03	1.10E+03
Land use	kg C deficit	3.34E+03	5.10E+03	9.08E+03	3.91E+03	4.24E+03	7.81E+03		4.93E+03	4.29E+03	4.66E+03
Water resource depletion	m^3 water eq	1.15E+02	1.51E+02	2.68E+02	1.19E+02	1.41E+02	2.83E+02		1.49E+02	1.40E+02	1.45E+02
Resource depletion	kg Sb eq	8.02E-02	1.11E-01	1.77E-01	1.62E-01	9.85E-02	1.99E-01		1.08E-01	1.25E-01	1.15E-01

Table 5
Annual environmental impact of a dwelling in EU. Results are reported per each dwelling type. A colour code is applied from lower impact (in green), to higher impact (in orange). colour scale.

Impact categories		SFH_ warm	SFH_ moderate	SFH_ cold	MFH_ warm	MFH_ moderate	MFH_ cold	Average SFH	Average MFH	EU housing average
Climate change	kg CO_2 eq	5.94E+03	7.79E+03	8.61E+03	3.91E+03	5.05E+03	4.97E+03	7.53E+03	4.65E+03	6.08E+03
Ozone depletion	kg CFC-11 eq	6.72E-04	9.66E-04	1.93E-03	4.44E-04	6.18E-04	1.06E-03	9.59E-04	5.82E-04	7.70E-04
Human toxicity, non-cancer effects	CTUh	6.80E-04	7.40E-04	1.39E-03	5.08E-04	4.84E-04	7.80E-04	7.57E-04	5.08E-04	6.32E-04
Human toxicity, cancer effects	CTUh	7.82E-05	9.61E-05	1.64E-04	6.17E-05	6.88E-05	1.06E-04	9.61E-05	6.84E-05	8.22E-05
Particulate matter	kg $PM_{2.5}$ eq	7.32E+00	8.07E+00	1.53E+01	5.33E+00	5.10E+00	8.20E+00	8.24E+00	5.35E+00	6.79E+00
Ionizing radiation HH	kBq U^{235} eq	5.32E+02	5.52E+02	1.13E+03	3.35E+02	3.79E+02	6.46E+02	5.73E+02	3.79E+02	4.75E+02
Photochemical ozone formation	kg NMVOC eq	1.35E+01	1.78E+01	2.78E+01	9.00E+00	1.17E+01	1.56E+01	1.76E+01	1.10E+01	1.42E+01
Acidification	molc H^+ eq	2.82E+01	3.94E+01	6.03E+01	1.83E+01	2.64E+01	3.40E+01	3.85E+01	2.40E+01	3.12E+01
Terrestrial eutrophication	molc N eq	4.39E+01	5.22E+01	9.48E+01	2.91E+01	3.42E+01	5.32E+01	5.27E+01	3.35E+01	4.30E+01
Freshwater eutrophication	kg P eq	3.79E-01	3.99E-01	8.10E-01	2.42E-01	2.80E-01	4.67E-01	4.13E-01	2.77E-01	3.45E-01
Marine eutrophication	kg N eq	3.99E+00	4.75E+00	8.70E+00	2.64E+00	3.12E+00	4.88E+00	4.79E+00	3.05E+00	3.92E+00
Freshwater ecotoxicity	CTUe	2.54E+03	3.27E+03	5.13E+03	1.87E+03	2.18E+03	3.06E+03	3.23E+03	2.12E+03	2.67E+03
Land use	kg C deficit	1.14E+04	1.38E+04	2.57E+04	7.93E+03	8.68E+03	1.31E+04	1.39E+04	8.66E+03	1.13E+04
Water resource depletion	m^3 water eq	3.93E+02	4.09E+02	7.59E+02	2.41E+02	2.89E+02	4.75E+02	4.21E+02	2.82E+02	3.51E+02
Mineral, fossil & ren resource depletion	kg Sb eq	2.75E-01	3.00E-01	5.00E-01	3.28E-01	2.02E-01	3.34E-01	3.04E-01	2.53E-01	2.78E-01

Table 6
Environmental impacts related to housing per person per year in EU (total and per lifecycle stage). A colour code is applied from lower impact (in green), to higher impact (in orange). Negative values in EoL are related to recycling benefits.

Impact category	Unit	Production	%	Constr.	%	Use	%	Mainten.	%	EoL	%	Total	%
Climate change	kg CO_2 eq	2.07E+02	8	2.14E+01	0.9	2.28E+03	91	3.27E+01	1.3	-3.42E+01	-1.4	**2.51E+03**	**100**
Ozone depletion	kg CFC-11 eq	1.29E-05	4	2.70E-06	0.8	2.95E-04	93	4.42E-06	1.4	2.52E-06	0.8	**3.18E-04**	**100**
Human toxicity, non-cancer effects	CTUh	3.40E-05	13	3.56E-06	1.4	2.17E-04	83	7.37E-06	2.8	-1.10E-06	-0.4	**2.61E-04**	**100**
Human toxicity, cancer effects	CTUh	1.39E-05	41	6.68E-07	2.0	1.85E-05	54	9.66E-07	2.8	-4.65E-08	-0.1	**3.39E-05**	**100**
Particulate matter	kg $PM_{2.5}$ eq	2.15E-01	8	1.91E-02	0.7	2.43E+00	87	1.22E-01	4.4	1.43E-02	0.5	**2.80E+00**	**100**
Ionizing radiation HH	kBq U^{235} eq	7.56E+00	4	1.52E+00	0.8	1.84E+02	94	2.09E+00	1.1	1.22E+00	0.6	**1.96E+02**	**100**
Photochemical ozone formation	kg NMVOC eq	6.22E-01	11	1.07E-01	1.8	5.00E+00	85	1.45E-01	2.5	7.18E-03	0.1	**5.88E+00**	**100**
Acidification	molc H^+ eq	8.66E-01	7	1.28E-01	1.0	1.13E+01	88	5.22E-01	4.0	4.06E-02	0.3	**1.29E+01**	**100**
Terrestrial eutrophication	molc N eq	1.94E+00	11	3.75E-01	2.1	1.46E+01	82	4.54E-01	2.6	3.79E-01	2.1	**1.78E+01**	**100**
Freshwater eutrophication	kg P eq	1.20E-02	8	1.04E-03	0.7	1.31E-01	92	1.54E-03	1.1	-2.76E-03	-1.9	**1.42E-01**	**100**
Marine eutrophication	kg N eq	1.71E-01	11	3.40E-02	2.1	1.34E+00	83	3.94E-02	2.4	3.58E-02	2.2	**1.62E+00**	**100**
Freshwater ecotoxicity	CTUe	2.12E+02	19	4.40E+01	4.0	7.80E+02	71	3.62E+01	3.3	3.05E+01	2.8	**1.10E+03**	**100**
Land use	kg C deficit	4.05E+02	9	5.54E+01	1.2	4.08E+03	87	1.61E+02	3.5	-3.81E+01	-0.8	**4.66E+03**	**100**
Water resource depletion	m^3 water eq	4.50E+00	3	7.30E-01	0.5	1.40E+02	97	5.12E-01	0.4	-6.90E-01	-0.5	**1.45E+02**	**100**
Resource depletion	kg Sb eq	2.13E-02	19	1.72E-03	1.5	6.61E-02	58	2.11E-02	18.3	4.72E-03	4.1	**1.15E-01**	**100**

Fig. 2. Contribution of the different life cycle phases of the BoP Housing to the different impact categories.

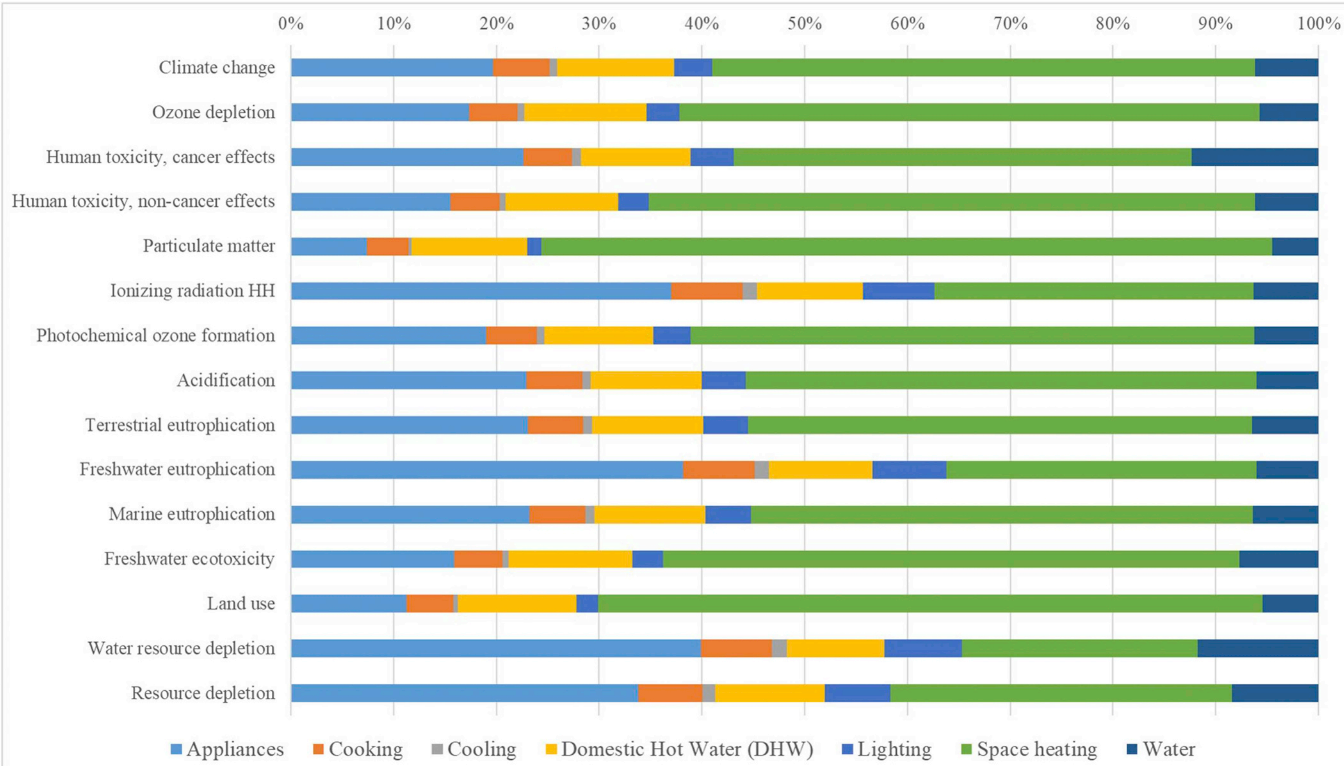


Fig. 3. Focus on the contribution of energy and water consumption to the impact of the use phases in the BoP Housing.

5.3. Annual environmental impact of the representative dwellings per square metre

One of the main objectives of the work was to develop a baseline scenario to be used as a reference for studies on environmental assessment of buildings. Considering that in many published LCA studies of buildings the functional unit is one square metre of usable/living floor area over one year (m^2/year) [6,51,66–68]), in this section the study adopts the same functional unit to show the results, with the aim to define a benchmark of a baseline scenario (current impacts) for testing improvements.

Concerning the dwelling size, statistical data about the average floor area per dwelling by dwelling type, by climate zone and by period of construction have been used to calculate the square metres per dwelling for each representative dwelling. Starting from the national data, the average values were calculated by dwelling type and by period of construction related to the three climatic zones (Tables S10 and S11). The calculations were made considering the number of dwellings in each Member State to define a "weighted" average in each climatic zone. The average floor area of each climatic zone was also calculated, as the weighted average of the average floor area of the different periods of construction.

Table 8 shows the characterisation results of the 24 representative dwellings related to one square metre of dwelling per year. The average annual impact of the production, construction, maintenance/replacement, use and end-of-life stages over the lifetime of the dwellings (100 years) is calculated, and then the overall value is divided by the size of each dwelling.

Since the energy consumption during the use phase is higher in cold than in warm climates and the use phase dominates the environmental impacts, the comparison between buildings of the same type (SFH or MFH) and same age of construction shows a predominance (a doubling for many impact indicators) of the environmental impacts of the dwellings in the cold climate zone and a lower environmental impact of the dwellings in the warm climate zone.

Table 8 also shows a tendency to a reduction of the impacts of dwellings built in recent years when comparing the same dwelling type in the same climate. This is due to their better thermal performance, i.e. to their lower energy consumption in the use phase. The implementation of energy efficiency measures allow greater reductions in some types of dwelling rather than in others. Nevertheless, it must be ascertained that interventions to save energy are not undermined by an increase of the impacts related to production, maintenance and disposal of materials used to improve energy performance.

It is important to highlight that even if the energy efficiency of dwellings increased significantly starting from 2000, this trend was largely offset by an increment of the housing space per person. The average area of a dwelling unit arose from 86 m^2 to 92 m^2 in the EU-15 between 1990 and 2007 [69], while the number of people per household decreased from 2.8 to 2.4 [41], giving a 20% rise in floor space per person and an increase in the number of households. In the EU-12 countries, the average floor area per dwelling increased even more rapidly, from 62 m^2 to 71 m^2 [70].

For this reason, the reduction of impacts due to better energy performance and related to similar dwellings in different periods but in the same climate area due is not always enough to compensate the increased impact caused by the grow in the dwelling size or by the square metres per person. For example, the overall impact of a SFH in a warm climate of 1990–2010 is similar to that of the SFH of 1970–1989, since the increase in terms of square metres of the dwelling (from 100 m^2/dwelling to 130 m^2/dwelling, see Table 1) offsets the decrease in energy consumption for heating, which drop from 76 kWh/m^2 in SFH of 1970–1989 to 62 kWh/m^2 in SFH of 1990–2010.

Finally, Table 8 also shows that the contribution of each group of representative dwellings is quite uniform for all indicators.

6. Discussion

In this section, the results are discussed and suggestions are made for policies toward a sustainable built environment.

Table 7
Normalized results per lifecycle stage. A colour code is applied from lower impact (in green), to higher impact (in orange).

Impact category	PRODUCTION	CONSTRUCTION	USE	Maintenance	EOL	TOTAL
Climate change	2.33E-02	2.42E-03	2.57E-01	3.69E-03	-3.85E-03	2.83E-01
Ozone depletion	5.97E-04	1.25E-04	1.37E-02	2.04E-04	1.16E-04	1.47E-02
Human toxicity, non-cancer effects	6.92E-02	7.24E-03	4.42E-01	1.50E-02	-2.24E-03	5.31E-01
Human toxicity, cancer effects	5.65E-01	2.72E-02	7.53E-01	3.93E-02	-1.89E-03	1.38E+00
Particulate matter	5.09E-02	4.52E-03	5.76E-01	2.89E-02	3.39E-03	6.64E-01
Ionizing radiation HH	6.27E-03	1.26E-03	1.53E-01	1.73E-03	1.01E-03	1.63E-01
Photochemical ozone formation	1.95E-02	3.35E-03	1.57E-01	4.57E-03	2.25E-04	1.85E-01
Acidification	1.78E-02	2.63E-03	2.33E-01	1.07E-02	8.34E-04	2.65E-01
Terrestrial eutrophication	1.06E-02	2.06E-03	8.03E-02	2.49E-03	2.08E-03	9.76E-02
Freshwater eutrophication	7.95E-03	6.92E-04	8.64E-02	1.02E-03	-1.83E-03	9.42E-02
Marine eutrophication	1.00E-02	2.00E-03	7.86E-02	2.32E-03	2.11E-03	9.51E-02
Freshwater ecotoxicity	2.55E-02	5.29E-03	9.38E-02	4.35E-03	3.67E-03	1.33E-01
Land use	1.39E-02	1.91E-03	1.40E-01	5.53E-03	-1.31E-03	1.60E-01
Water resource depletion	5.65E-02	9.16E-03	1.75E+00	6.42E-03	-8.66E-03	1.82E+00
Resource depletion	3.70E-02	2.99E-03	1.15E-01	3.66E-02	8.20E-03	2.00E-01

Table 8
Characterised results of the 24 representative dwellings of Basket of Products Housing. Results are reported for one square metre of floor area over one year. A colour code is applied from lower impact (in green), to higher impact (in orange).

Impact category	Unit	SFH_warm_<1945	SFH_warm_1945-69	SFH_warm_1970-89	SFH_warm_1990-2010	SFH_moderate_<1945	SFH_moderate_1945-69	SFH_moderate_1970-89	SFH_moderate_1990-2010	SFH_cold_<1945	SFH_cold_1945-69	SFH_cold_1970-89	SFH_cold_1990-2010
Climate change	kg CO_2 eq	6.30E+01	6.17E+01	5.59E+01	4.41E+01	9.99E+01	8.98E+01	7.60E+01	6.22E+01	8.88E+01	8.57E+01	7.30E+01	6.59E+01
Ozone depletion	kg CFC-11 eq	7.15E-06	6.99E-06	6.31E-06	4.98E-06	1.25E-05	1.12E-05	9.44E-06	7.56E-06	2.02E-05	1.92E-05	1.64E-05	1.41E-05
Human toxicity, non-cancer effects	CTUh	7.51E-06	7.30E-06	6.12E-06	4.88E-06	9.46E-06	8.57E-06	7.21E-06	5.93E-06	1.46E-05	1.38E-05	1.19E-05	1.02E-05
Human toxicity, cancer effects	CTUh	8.29E-07	8.23E-07	7.30E-07	5.80E-07	1.17E-06	1.11E-06	9.41E-07	8.37E-07	1.69E-06	1.63E-06	1.41E-06	1.25E-06
Particulate matter	kg $PM_{2.5}$ eq	8.15E-02	7.85E-02	6.49E-02	5.33E-02	1.05E-01	9.29E-02	7.92E-02	6.27E-02	1.61E-01	1.52E-01	1.31E-01	1.09E-01
Ionizing radiation HH	kBq U235 eq	5.48E+00	5.42E+00	5.15E+00	4.04E+00	6.72E+00	6.28E+00	5.45E+00	4.83E+00	1.17E+01	1.13E+01	9.56E+00	8.66E+00
Photochemical ozone formation	kg NMVOC eq	1.44E-01	1.41E-01	1.27E-01	1.00E-01	2.27E-01	2.05E-01	1.74E-01	1.45E-01	2.87E-01	2.75E-01	2.37E-01	2.10E-01
Acidification	molc H^+ eq	2.96E-01	2.91E-01	2.67E-01	2.11E-01	4.96E-01	4.50E-01	3.88E-01	3.24E-01	6.11E-01	5.88E-01	5.17E-01	4.81E-01
Terrestrial eutrophication	molc N eq	4.64E-01	4.55E-01	4.16E-01	3.26E-01	6.53E-01	5.99E-01	5.12E-01	4.37E-01	9.82E-01	9.41E-01	8.07E-01	7.14E-01
Freshwater eutrophication	kg P eq	3.90E-03	3.86E-03	3.68E-03	2.88E-03	4.83E-03	4.52E-03	3.95E-03	3.53E-03	8.35E-03	8.08E-03	6.86E-03	6.23E-03
Marine eutrophication	kg N eq	4.21E-02	4.13E-02	3.78E-02	2.96E-02	5.95E-02	5.45E-02	4.66E-02	3.97E-02	9.02E-02	8.64E-02	7.41E-02	6.55E-02
Freshwater ecotoxicity	CTUe	2.70E+01	2.65E+01	2.36E+01	1.91E+01	4.09E+01	3.75E+01	3.20E+01	2.73E+01	5.31E+01	5.08E+01	4.39E+01	3.85E+01
Land use	kg C deficit	1.25E+02	1.22E+02	1.04E+02	8.30E+01	1.79E+02	1.59E+02	1.36E+02	1.08E+02	2.68E+02	2.56E+02	2.19E+02	1.89E+02
Water resource depletion	m3 water eq	3.99E+00	3.97E+00	3.87E+00	3.00E+00	4.92E+00	4.65E+00	4.07E+00	3.60E+00	7.77E+00	7.57E+00	6.39E+00	5.93E+00
Resource depletion	kg Sb eq	2.76E-03	2.74E-03	2.67E-03	2.23E-03	3.51E-03	3.33E-03	3.02E-03	2.78E-03	5.14E-03	4.95E-03	4.26E-03	3.82E-03

Impact category	Unit	MFH_warm_<1945	MFH_warm_1945-69	MFH_warm_1970-89	MFH_warm_1990-2010	MFH_moderate_<1945	MFH_moderate_1945-69	MFH_moderate_1970-89	MFH_moderate_1990-2010	MFH_cold_<1945	MFH_cold_1945-69	MFH_cold_1970-89	MFH_cold_1990-2010	Impact/m² (average EU dwelling)
Climate change	kg CO_2 eq	4.85E+01	4.78E+01	4.04E+01	3.44E+01	5.67E+01	5.68E+01	4.68E+01	4.12E+01	8.43E+01	8.43E+01	8.24E+01	7.87E+01	6.39E+01
Ozone depletion	kg CFC-11 eq	5.53E-06	5.44E-06	4.56E-06	3.85E-06	6.94E-06	6.96E-06	5.77E-06	5.00E-06	1.83E-05	1.83E-05	1.76E-05	1.63E-05	8.15E-06
Human toxicity, non-cancer effects	CTUh	6.38E-06	6.27E-06	5.20E-06	4.37E-06	5.38E-06	5.40E-06	4.52E-06	4.00E-06	1.33E-05	1.33E-05	1.28E-05	1.26E-05	6.69E-06
Human toxicity, cancer effects	CTUh	7.43E-07	7.40E-07	6.43E-07	5.68E-07	7.27E-07	7.28E-07	6.65E-07	6.26E-07	1.81E-06	1.81E-06	1.76E-06	1.68E-06	8.69E-07
Particulate matter	kg $PM_{2.5}$ eq	7.14E-02	6.97E-02	5.18E-02	4.14E-02	5.81E-02	5.83E-02	4.68E-02	4.01E-02	1.42E-01	1.42E-01	1.35E-01	1.23E-01	7.18E-02
Ionizing radiation HH	kBq U235 eq	3.96E+00	3.92E+00	3.59E+00	3.13E+00	4.04E+00	4.04E+00	3.66E+00	3.41E+00	1.10E+01	1.10E+01	1.07E+01	1.02E+01	5.02E+00
Photochemical ozone formation	kg NMVOC eq	1.11E-01	1.10E-01	9.27E-02	7.95E-02	1.31E-01	1.32E-01	1.08E-01	9.56E-02	2.66E-01	2.66E-01	2.58E-01	2.43E-01	1.50E-01
Acidification	molc H^+ eq	2.23E-01	2.21E-01	1.92E-01	1.65E-01	2.92E-01	2.93E-01	2.47E-01	2.21E-01	5.75E-01	5.75E-01	5.67E-01	5.40E-01	3.29E-01
Terrestrial eutrophication	molc N eq	3.56E-01	3.51E-01	3.04E-01	2.61E-01	3.79E-01	3.80E-01	3.20E-01	2.89E-01	9.08E-01	9.08E-01	8.80E-01	8.30E-01	4.55E-01
Freshwater eutrophication	kg P eq	2.82E-03	2.80E-03	2.63E-03	2.28E-03	3.00E-03	3.00E-03	2.69E-03	2.52E-03	7.92E-03	7.92E-03	7.75E-03	7.45E-03	3.64E-03
Marine eutrophication	kg N eq	3.22E-02	3.18E-02	2.75E-02	2.36E-02	3.45E-02	3.46E-02	2.91E-02	2.63E-02	8.34E-02	8.34E-02	8.08E-02	7.62E-02	4.14E-02
Freshwater ecotoxicity	CTUe	2.28E+01	2.25E+01	1.95E+01	1.69E+01	2.38E+01	2.38E+01	2.06E+01	1.87E+01	5.21E+01	5.21E+01	5.05E+01	4.83E+01	2.82E+01
Land use	kg C deficit	1.04E+02	1.02E+02	7.83E+01	6.36E+01	9.84E+01	9.86E+01	8.01E+01	6.90E+01	2.26E+02	2.26E+02	2.15E+02	1.98E+02	1.19E+02
Water resource depletion	m3 water eq	2.75E+00	2.74E+00	2.63E+00	2.33E+00	3.04E+00	3.04E+00	2.81E+00	2.66E+00	8.54E+00	8.54E+00	7.32E+00	7.08E+00	3.71E+00
Resource depletion	kg Sb eq	2.16E-03	2.15E-03	4.68E-03	4.83E-03	2.12E-03	2.12E-03	1.96E-03	1.86E-03	4.87E-03	4.87E-03	4.76E-03	9.42E-03	2.94E-03

The awareness of the current average impacts can enable institutional decision-makers to simulate the environmental effects of any building stock redevelopment strategies (different retrofit options, regeneration as opposed to demolition and new building construction, promotion of bio-based materials, etc.) and to identify the most effective solutions for reducing the overall environmental impacts.

To this end, critical issues highlighted in the results include the relative impact of the use phase, particularly in connection with energy consumption for space heating. The effect of the European Directive energy performance of buildings (EPBD) is not depicted in this study, because its baseline year (2010) is the first year of implementation of the Directive. It should also be pointed out that the construction of new buildings (adapted to the new regulations) faced a setback due to the economic crisis of 2009 and the current housing stock in Europe is increased at a rate of only 1.1% per year. Even existing buildings continue to be upgraded at a very low rate, of only 1.2% [71]. This unsatisfactory rate may negatively impact the achievement of 20-20-20 objectives. For this reason it is necessary to promote intervention policies on the existing building stock (e.g., using tax incentives), considering that the old high-energy buildings still play the most important role in energy consumption. Nevertheless, it is important to promote the retrofit strategies with a reduction of impacts in the whole life cycle, referring not only on the use phase.[8] For this purpose, the use of LCA method to verify the environmental effectiveness of strategies and policies is an important issue. The representative dwellings modelled in this study can be used to verify the environmental effects of policies (e.g. incentives for insulation or replacement of windows and systems) and of actions on the building stock (such as levels of thermal insulation, kind of materials and technical building systems, type of energy source), in order to avoid burden shifting (from the use to the production phase or from one impact category to another).

Another critical issue that emerged in this study was the dependence of energy production on fossil fuel sources. About that, there are many European policies in place. However, often no assessments are made to evaluate the overall environmental impacts generated by a given energy source: for example, the present research have highlighted potentially critical environmental issues (e.g. particulate matter emission) connected to the use of biomass and waste-to-energy, which are conversely widely promoted in Europe.

Besides, an important issue is whether it is more appropriate to refurbish or to demolish and rebuild a dwelling [72–74]. The results of this study show that the production phase accounts for a significant portion of the environmental impacts of buildings (up to 40%) and highlight the importance of upgrading existing buildings rather than demolishing and rebuilding them. In the case of demolition and reconstruction, it should be pointed out that the impacts of the end-of-life of the demolished building must be considered in addition to the impacts of the new construction. Since about 50% of the impacts of production-construction and end-of-life concern the load-bearing structure of buildings (particularly steel and concrete), in order to contain environmental impacts, it is essential to maintain at least the load-bearing structure, retrofitting the envelope (unless there are serious structural problems in the building or serious functional problems in the space distribution).

Finally, it is important to highlight the potential trade-off between, on one hand, space provision and occupants' health and wellbeing and, on the other, resource use in the construction phase and in the use phase. The risk is that to reduce impacts the optimal solution is minimized (low resource consumption but also low performance level): for instance, lower impacts can correspond to a solution with less space per person. For this reason, special attention should be paid to avoid the reduction of the environmental impacts without considering health and wellbeing consequences.

Overall, results should be critically considered. For example, modelling choices, such as conducting an attributional LCA for 100 years, as well as the subjectivity of the selection of a specific normalisation and weighting should be taken intro account. A sensitivity analysis may be performed on those aspects, e.g. when running scenarios which aims at assessing the improvement potential of a specific intervention or innovation.

7. Conclusions

The overall results indicate that in the majority of the impact categories the most impactful dwelling model is the Single-Family House in the cold climate. The use phase is the most impacting lifecycle stage of the BoP-housing (over 80% of impacts in 11 impact categories out 15), due to the contribution of burning fossil fuels for heating and electricity production. The production phase of construction materials follows in importance (from 3% to 40%, depending on the impact categories), especially for the production of steel, ceramic tiles, concrete and bricks. A small contribution also comes from the end-of-life phase, where the impacts never exceeds 4% for all indicators. Small benefits (−1.9%) come from the recycling of building materials at the end of life. However, when looking at the entire building stock, the majority of the impacts are related to the Single Family House in moderate climate, followed by the Multi Family House in moderate climate.

From the hotspot analysis developed to identify the most relevant impact categories for the housing BoP, it emerged that the three most relevant categories are: Water depletion (mainly due to water used in electricity production), Resource depletion (mainly due to the production of ceramic tiles and electricity), and Human toxicity (mainly due reinforcing steel).

The assessment of the environmental impacts associated with the residential buildings in Europe is a worthy outcome, allowing the assessment of the current building stock, the definition of a baseline simulate against which assessing eco-innovation scenarios to reduce impacts.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.buildenv.2018.09.008.

[8] In the last few years, insulation and wall thicknesses significantly bumped up in order to guarantee high thermal performance values, increasing as a consequence the associated impacts. Also building services are increasing exponentially: ducts for mechanical ventilation, ducts for the rainwater recovery, systems for the renewable energy production are planned to decrease the consumption in the use phase, without verifying the impacts related to the production phase and the balance of impacts in the whole life cycle (considering also maintenance and end of life). As a result, the balance between the advantages pertaining to a reduction in consumption during the use phase and the disadvantages pertaining to increased impacts due to the production of materials/systems would appear to be essential if effective solutions from the environmental perspective want to be identified.

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