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Environmental benchmarks for buildings

EFIResources*:*
Resource Efficient Construction towards Sustainable Design

Gervasio, H. & Dimova, S.

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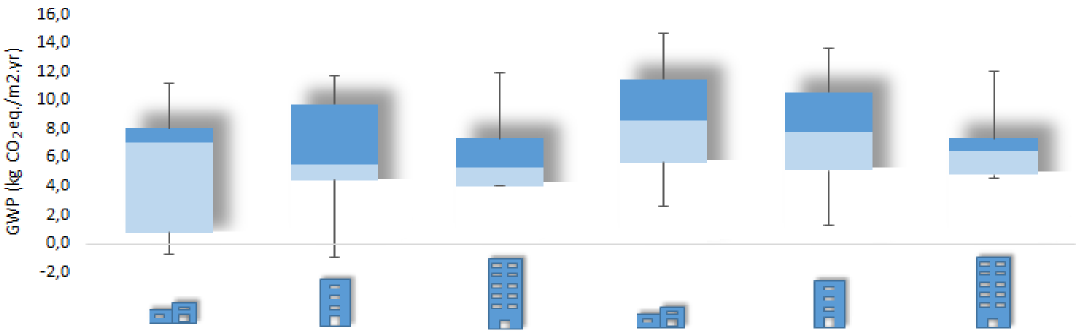

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Contact information
Name: Silvia Dimova
Address: European Commission, Joint Research Centre, Directorate E, Unit E.4
Email: silvia.dimova@ec.europa.eu
Tel.: +39 0332 78 9063

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Authors

Helena Gervasio, Silvia Dimova

Abstract

The research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, supports European policies related to the efficient use of resources in construction and its major goal is the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings in the early stages of building design.

In the proposed approach for sustainability design, the performance of a building, focussing on resource use, is benchmarked against standard and/or best practices. Therefore, benchmarks for the environmental performance of buildings are developed, providing a consistent and transparent yardstick for the assessment of the environmental performance of buildings and striving towards an effective reduction of the use of resources and relative environmental impacts in the building sector.

This report focusses on the framework for the development of benchmarks for the life cycle performance of buildings and provides a preliminary set of benchmarks for residential buildings, which may be considered to be representative of the existing residential building stock in Europe.

1 Introduction

The built environment is responsible for a high global share of environmental, economic and social impacts. An enhanced construction in the EU would influence 42% of our final energy consumption, about 35% of our greenhouse gas emissions, more than 50% of all extracted materials and enable savings of water up to 30% [1]. Therefore, the standard way in which construction of buildings is currently performed is jeopardizing the chances for future generations to meet their own needs.

The research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, launched in September 2016, aims to support European policies related to the efficient use of resources in construction and its major goal is the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings in the stage of building design.

The results of this project will facilitate the incorporation of sustainability criteria in construction practice in consistency with the safety requirements of the design standards, thus providing building designers with a tool for safe and clean construction.

The work plan of the project is organized into four main tasks:

- Task 1: Development of a life cycle model for the assessment of buildings, which will enable to perform the life cycle analysis of the cases studies and benchmarking;
- Task 2: Identification of best practices and development of a set of benchmarks for residential and office buildings;
- Task 3: Development of an approach for sustainable design consistent with the reliability approach of the Eurocodes;
- Task 4: Recommendations for standardization and guidelines for sustainable design.

This report corresponds to the work developed in the 2nd task of the project and aims to establish the general framework for the development of benchmarks and to provide a set of preliminary benchmarks for the life cycle analysis (LCA) of buildings. The benchmarks are evaluated based on the LCA model developed in the 1st task of the project [2].

Hence, the report is organized into the following sections: Section 2 provides a brief background on the benchmarking for buildings and establishes the general framework for the development of benchmarks; in Section 3, available benchmarks from a literature review are provided; a preliminary set of benchmarks calculated based on the model developed in the 1st task of the project is provided in Section 4 and these values are compared with the values from the literature review; finally, in Section 5 conclusions are drawn in relation to the set of values provided in this report and on potential improvements of these values, which will be addressed in the next task of the project.

2 Background and framework for benchmarking

2.1 Why the benchmarking of buildings?

The project *EFIResources* focus on resource efficiency in the building sector. In this project, resource efficiency is understood as a reduction of the use of resources in buildings and relative environmental impacts, over the complete life cycle of the building [2]. Therefore, in order to measure such reduction and thus assess the efficiency of buildings, reference values or benchmarks are needed. Hence, a benchmark is here understood as a point of reference to enable comparisons; while benchmarking is the process that assesses and compares the performance of a building against the benchmarks.

Benchmarks are used to monitor the changes and/or progress in the different sectors induced by EU directives. For instance, in relation to the energy consumption of buildings, during the use stage (the operational energy), the EU has adopted a number of measures to improve the energy efficiency of buildings. Following the implementation of such measures, energy efficiency certificates are now mandatory for the sale and rental of buildings, which benchmarks the energy consumption of buildings during the operation stage. This was a crucial step towards the effective reduction of the operational energy of buildings and to enable the setting of ambitious targets for energy efficiency by 2020 and onwards [3].

Moreover, a benchmarking initiative in the US [4], for the energy consumption of buildings, enables building owners and occupants to benchmark the energy consumption of their properties, based on the monthly energy bill, with other similar properties. This has been leading to significant reductions in terms of the energy consumption but also to an increased awareness and demand for energy-efficient properties. Thus, in this case, benchmarking is used as a policy tool for forcing the real estate market to properly value energy efficiency.

Benchmarking is also commonly used in rating systems for the ecological labelling of buildings such as LEEDS, BREEAM, HQE, SBTool, DGNB, etc. In these tools, the evaluation of the performance of a building, based in selected criteria, is compared with pre-defined thresholds or reference values. Quantitative and qualitative indicators are then translated into grades that are further aggregated into a final score. The main drawbacks of these systems were highlighted in [2], but the most relevant one is that these systems do not enable comparability due to disparities in scope of analysis and methodologic choices.

Hence, the main goal for the development of the benchmarks is to develop a consistent and transparent yardstick to assess the environmental performance of buildings, striving towards an effective reduction of the use of resources and relative environmental impacts in the building sector.

2.2 General framework for the benchmarks

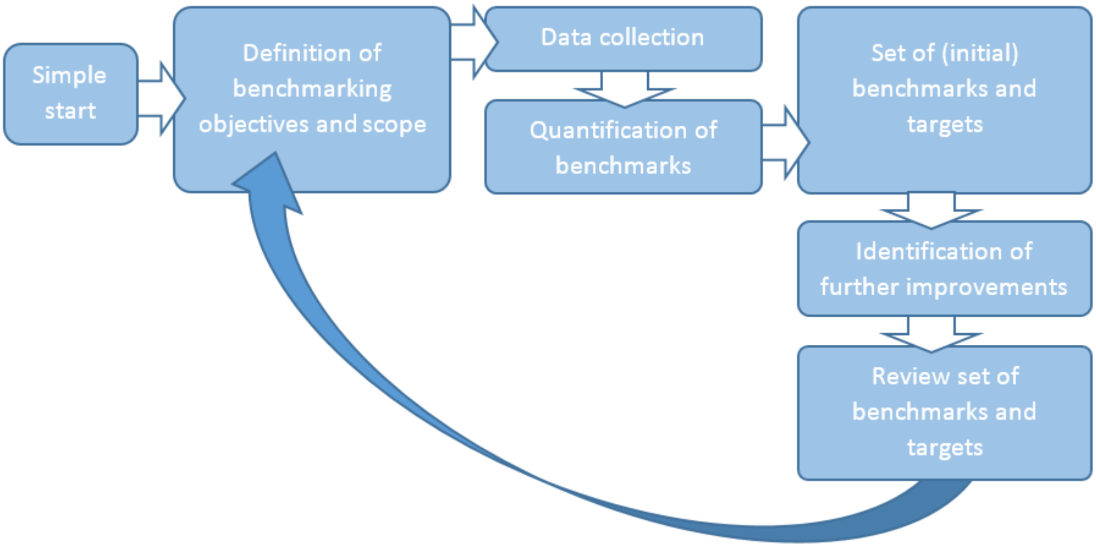
2.2.1 Graduated approach

One of the key steps in the development of benchmarks is the collection of accurate, consistently measured and verifiable data [5]. However, as stressed out in [2], in relation to buildings, data availability and collection are usually limiting the scope and accuracy of the life cycle assessment of buildings.

Thus, following guidance in [5], a graduated approach is herein adopted for the benchmarks, starting on a simple basis and being refined and increasing in complexity over time, as data collection on buildings and relative processes becomes more complete and precise.

Hence, the benchmarking of buildings is an evolving process in sophistication and complexity, starting from simple data and improving the initial set of benchmarks with time, as illustrated in Figure 1.

Figure 1. Graduated approach for benchmarking of buildings (based in [5])



In the follow-up of this project, a database is foreseen for the collection of building data (e.g. Bill-of-Materials of buildings, plans, etc.), which will enable to continuously update the values that will be provided by the end of the current project, thus increasing the accuracy of these values and the reliability of the approach over time.

2.2.2 Definition of objectives and scope

The sustainable design approach proposed in the project *EFIResources* aims for the harmonization between environmental criteria and structural criteria in the design of buildings, leading to an enhanced building design that copes with required safety demands, but with lower pressure on the environment and on the use of natural resources.

In the European codes for structural design, the Eurocodes, a limit state approach is adopted, in which the actual performance of the structure (S) is compared to an acceptable or targeted performance (R), and failure is expressed by $R < S$.

To be in line with the above approach, a similar procedure is proposed in this project, which relates the environmental performance of a building (S_{env}) to values referring to standard and/or best practices (R_{env}). Hence, the main goal of the benchmarks it to enable such comparison. Furthermore, target values may be defined taking into account that the final goal of the approach is the improvement of the performance of the building in terms of the use of resources and relative environmental impacts.

The assessment of the environmental performance of buildings, which is based on life cycle analysis entailing all stages throughout the lifetime of buildings, is limited to the structural system or frame of the building, including the foundations. Moreover, currently only two types of buildings are addressed: residential and office buildings.

However, the scope of the analysis may be expanded in the future, in order to account for the complete building and other building typologies.

2.2.3 Data collection

The definition of benchmarks entails the collection of two different types of data: (i) the collection of building data, which includes quantities of materials and list of processes considered in the scope of the analysis, throughout the life cycle of the building; and (ii) the collection of environmental data for the quantification of potential environmental impacts.

In relation to the first type of information, data is preferably collected from design offices or building promoters, and consists on the Bill of Materials (BoM) produced for bidding purposes. This data can be provided directly from software platforms like BIM. Additional information for the definition of realistic scenarios that are needed for the assessment of the different life cycle stages of the building, should preferably be provided and/or discussed with building professionals.

In this project, building data was collected from design offices, building promoters and research centres, acknowledged in this report, but also from other sources in the literature.

However, the preliminary set of benchmarks provided in this report is based on building data from the *IMPRO-Building* project [6]. This project aimed for the identification of environmental improvement potentials of residential buildings in the EU-25 and therefore, all relevant types of residential buildings were taken into account: single-family (SI) houses, multi-apartment buildings (MF) and high-rise buildings (HR). Building data provided in this project represented 53%, 37% and 10%, respectively for SI, MF and HR, of the existing EU-25 building stock.

Since, the data provided in the *IMPRO* project is mostly referring to existing buildings in the EU, the construction year varies from second half of the 20th century (although a few cases are from the beginning of the century) to the beginning of the 21st century, the preliminary set of benchmarks provided in this report may be considered to be representative of the existing residential building stock in Europe.

On the other hand, building data collected from design offices, building promoters and research centres, is referring to recent buildings, and this data will be used to improve the preliminary set of benchmarks provided in this report and to identify best practices in the building sector. The analysis of this data is not included in this report.

In relation to the second type of information, data for the environmental assessment of buildings may be collected from generic databases for LCA and from Environmental Product Declarations (EDPs). In the project *EFIResources*, both sources of data are used in the calculation of the benchmarks. Both sources of data and respective quality requirements were described in [2].

2.2.4 Quantification of the environmental performance of buildings

To assure consistency in the development of the benchmarks it is crucial that all calculations are based on the same methodological choices and on the same quality of data.

Hence, the model developed for the life cycle assessment of buildings, leading to the definition of the set of benchmarks, is based on the standardized framework for LCA developed by CEN TC 350 for the sustainability assessment of construction works. In this case, as the assessment is made at the building level, the most relevant standard is EN 15978 [8].

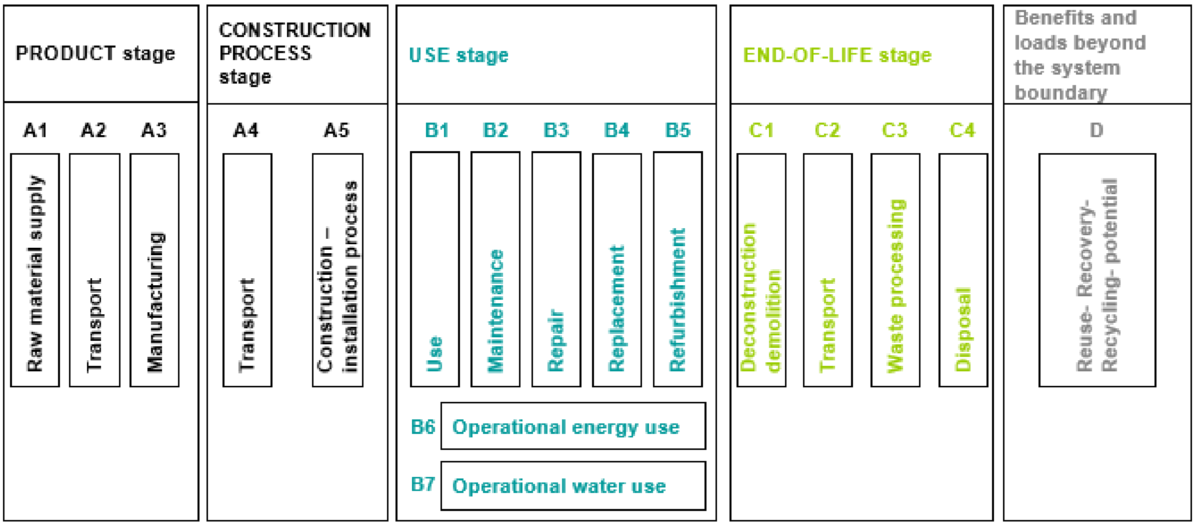
The adoption of a standardized procedure ensures the use of a consistent approach, which was developed specifically for the assessment of construction works, thus enabling comparability and benchmarking.

A description of this model and its implementation into a professional software for LCA, are fully provided in [2]. Therefore, in this sub-section, only the most relevant aspects are addressed.

As already referred, the scope of the analysis takes into account the complete life cycle of the building, from the product stage to the end-of-life stage. To provide full transparency of the results, data is not aggregated throughout the life cycle of the building. As illustrated in Figure 2, the potential environmental impacts occurring over the life cycle of the building are allocated to the stage in which they occur, according to EN 15978.

Hence, a set of benchmarks will be defined for each Module in the scope of LCA of buildings, although life cycle aggregated results will also be provided. It is noted that usually Modules A1 to A3, corresponding to a cradle-to-gate analysis (C2Gt) are usually aggregated in LCA communications and reports, and this will also be the case in this report.

Figure 2. Scope of the LCA of buildings according to CEN TC350 standards [8]



The benchmarks for the assessment of the environmental performance of buildings are based on two types of environmental indicators [8]: (i) indicators focussing on impact categories using characterisation factors, and (ii) indicators focussing on environmental input and output (I/O) flows. Both types of indicators are indicated in Table 1.

The list of indicators provided in Table 1, covers most flows and environmental problems that are currently considered in other similar approaches for LCA, as discussed in [2].

The framework for the assessment of the environmental performance of buildings, briefly described in the above paragraphs, provides a consistent and transparent basis for the definition of benchmarks. However, it is observed that this framework is flexible enough to allow the extension of its scope and the inclusion of other indicators that might become relevant for the performance of buildings, including economic and social aspects.

2.2.5 Setting of benchmarks

For the development of benchmarks, quantitative information is needed related with the environmental performance of buildings, to enable the definition of reference values or sustainability levels. Different information sources may be considered, which depend on the purpose of the benchmarks [7]:

- Hence, when the purpose is to establish politic targets or strategies, then target values are pursued, which are often related to economic, technical or environmental optimum considerations;
- On the other side, when the purpose is to establish limit values to be prescribed by codes and standards, then limit values may be defined by the lowest acceptable value, representing the minimum acceptable performance;
- When the aim is to promote an improved environmental building design, then reference values and/or best values may be provided by the statistical analysis of an appropriate set of data.

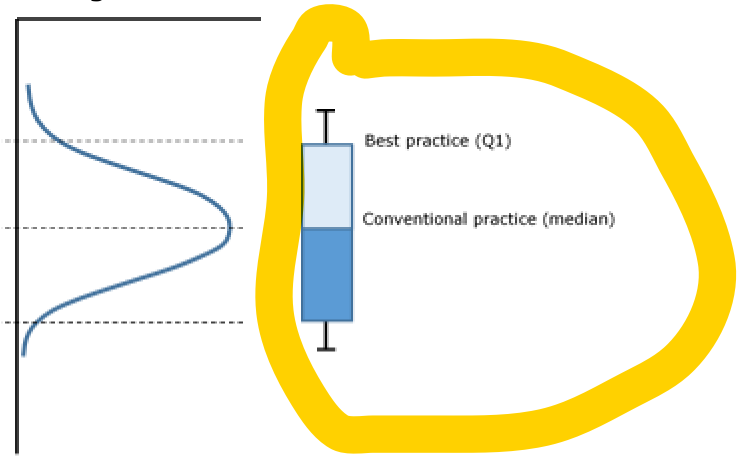
Table 1. Indicators describing environmental impacts and I/O flows [8]

Input/Output flows		Unit
(I) Use of renewable primary energy excluding energy resources used as raw material		MJ, net calorific value
(I) Use of renewable primary energy resources used as raw material		MJ, net calorific value
(I) Use of non-renewable primary energy excluding primary energy resources used as raw material		MJ, net calorific value
(I) Use of non-renewable primary energy resources used as raw material		MJ, net calorific value
(I) Use of secondary material		kg
(I) Use of renewable secondary fuels		MJ
(I) Use of non-renewable secondary fuels		MJ
(I) Net use of fresh water		m^3
(O) Hazardous waste disposed		kg
(O) Non-hazardous waste disposed		kg
(O) Radioactive waste disposed		kg
(O) Components for re-use		kg
(O) Materials for recycling		kg
(O) Materials for energy recovery (not being waste incineration)		kg
(O) Exported energy		MJ for each energy carrier
Environmental impacts	**Abbreviation**	**Unit**
Global Warming Potential	GWP	kg CO_2 eq.
Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 eq.
Acidification potential of land and water	AP	kg SO_2- eq.
Eutrophication potential	EP	kg PO_4^{3-} eq.
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg C_2H_4 eq.
Abiotic Resource Depletion Potential for elements	$ADP_{elements}$	kg Sb eq.
Abiotic Resource Depletion Potential of fossil fuels	$ADP_{fossil\ fuels}$	MJ, net calorific value

In the scope of the project *EFIResources*, benchmarks will be developed, based on the statistical analysis of a sample of buildings collected in the project.

Moreover, 'conventional' practice (also known as 'business as usual') is assumed to be given by the median value of the environmental performance of the buildings (represented by any of the indicators in Table 1); while, 'best practice' is assumed to be given by the value of the environmental performance that is achieved by only 25% of the buildings, i.e., the upper limit of the first quartile, as illustrated in Figure 3.

Figure 3. 'Conventional' and 'best' values



It is important to highlight that the quality and robustness of benchmarks based on a statistical analysis is strongly dependent on the quality and representativeness of the sample in relation to the 'basic population'.

2.3 Differentiation factors for benchmarking

The design of a building depends of local conditions, technical and functional requirements from safety regulations and/or client's specific requirements. Therefore, the environmental performance of buildings will also be influenced by the same factors and the definition of benchmarks should also take into account these differentiation factors.

In the following paragraphs, the main aspects that may influence the design of a building and the respective environmental performance are discussed.

2.3.1 Building typology and other characteristics

Although, in special cases, general benchmarks set for large groups of buildings (e.g. residential buildings) are useful, it is important that benchmarks are defined for smaller groups, with more specific characteristics (e.g. single houses or apartment blocks).

Thus, to enable the definition of benchmarks at more specific levels of detail, the following information was collected for each building (whenever available):

- Type of building;
- Location of building;
- Total Gross Floor Area (in m^2);
- Number of floors;
- Number of occupants/working places;
- (Estimated) design working life (in years);
- Building ref. year;
- Location of building;
- Seismic area;
- Climatic area.

In relation to building typology, in the scope of this project, the focus is given to residential and office buildings. Moreover, for residential buildings, three different types of buildings are considered: single family houses, multi-family houses ($\leq$ 5 storeys) and multi-storey buildings (> 5 storeys).

In case of a residential building, the number of occupants refers to the number of people living inside the building on a permanent basis; while, in case of an office building, the number of occupants or working places refers to the number of people working in the building or the number of the respective working places.

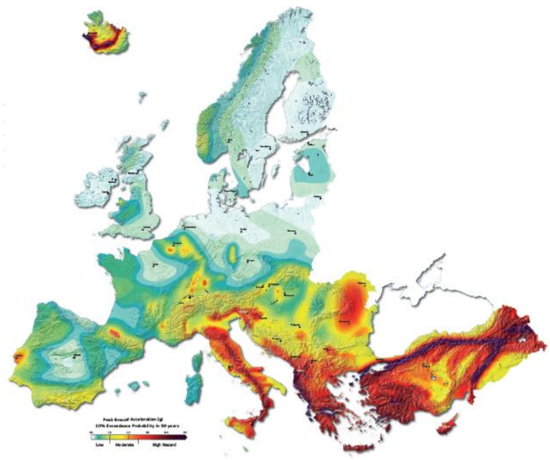
The (estimated) design working life corresponds to the reference period for the life cycle analysis, and the building reference year is the year corresponding to the design of the building or to the construction of the building (when applicable).

The seismic area may be identified by the reference ground acceleration of the location of the building, see sub-section 2.3.2; while, the climatic area may be identified by the *Köppen-Geiger* climate classification, see sub-section 2.3.3.

2.3.2 Seismic loading constraints

One of the design loads prescribed in the structural codes for building design is the seismic load. The severity of this load depend on the building location. In locations prone to seismic events, the seismic load may be governing the design of the building. In such locations, structures are required to bear proper stiffness and load-bearing capacity to resist frequent earthquakes, and possess proper ductility and energy-dissipating capacity to avoid collapse, in case of rare earthquakes [9]. Hence, the seismic design influences the way the structure is conceived and consequently, the quantities of materials that are required.

Figure 4. European seismic hazard map [10]



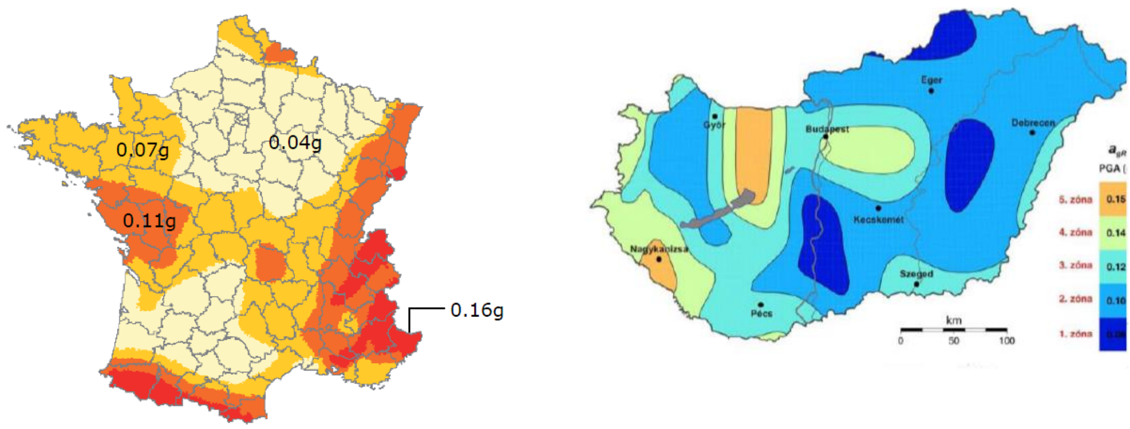
Therefore, the definition of benchmarks for buildings should take this into account, as the vulnerability of buildings to seismic hazards varies across European countries, as observed from Figure 4.

The hazard map in Figure 4 displays the Peak Ground Acceleration (PGA) (with a period of return of 475 years) in Europe for buildings [10].

In this case, low hazard areas (PGA ≤ 0.1g) are coloured in blue-green, moderate hazard areas in yellow-orange and high hazard areas (PGA > 0.25g) in red.

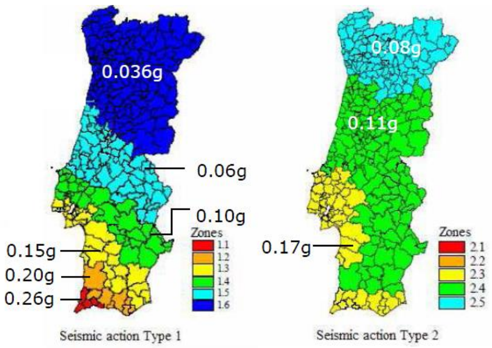
The reference standard in Europe for the seismic design of buildings is the Eurocode 8 [11], which establishes the requirements for structures to ensure that, in the event of earthquakes, human lives are protected and damage is limited. This code recommends to map the seismic zones of Member State (MS) countries in terms of the reference ground acceleration, and most MS have already complied with this recommendation, as illustrated in Figure 5 for some countries.

Figure 5. Seismic zone maps adopted by EU Member States [12]

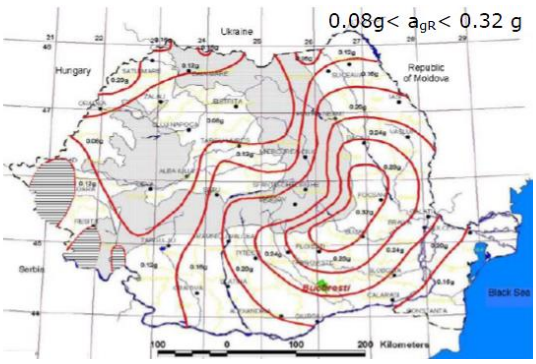


(a) France

(b) Hungary



(c) Portugal



(d) Romania

Hence, in the quantification of the benchmarks for the buildings, the information about the location of the building should be specified, according to the respective national seismic map (when available).

2.3.3 Climatic constraints

The climate is a key-factor for the energy consumption of buildings. Besides the direct influence of the climate on the energy needs for heating and cooling, the specific location of the building is also responsible for other types of energy consumption, like the increased energy requirements for building illumination when the number of daylight hours decreases [13].

The design of a building should take into account the climatic characteristics where the building is supposed to be built, in order to comply with normative energy requirements.

Taking as example the Köppen-Geiger climate classification [14], in Europe four general climatic regions may be identified, as illustrated in Figure 6: (i) regions with lower latitudes (below 45ºN) of southern Europe, in which the climate is labelled as Csa and Csb; (ii) western central European countries, where the climate is mainly classified as Cfb; (iii) eastern central European countries, classified as Dfb; and (iv) regions with higher latitudes (above 55ºN), the Nordic European countries, in which the climate is mostly frequently labelled as Dfc.

As observed in Figure 6, a building designed for a southern European country has to cope with warm temperatures, dry and hot summers; whereas, buildings in northern countries have to cope with low temperatures, humidity and cool summers. Therefore, in general, a building designed for a southern country is not appropriate for a northern country and vice-versa.

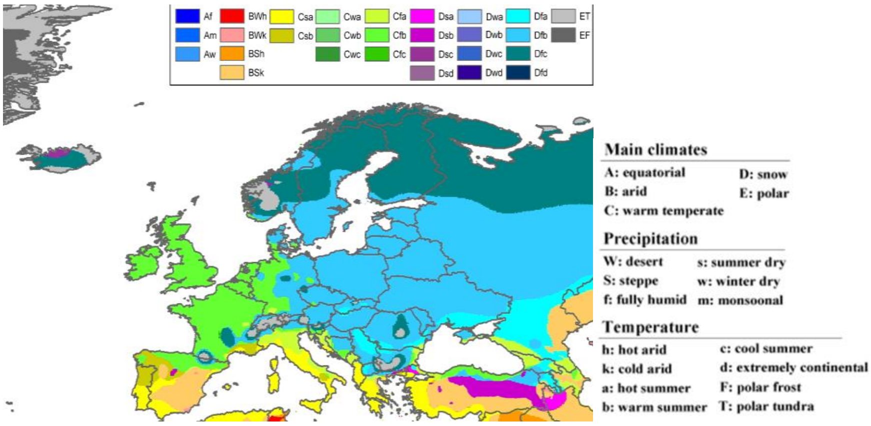
These differences are illustrated by the example provided in the following paragraphs.

A LCA was performed for 76 buildings located in 3 main climatic zones in Europe, according to the respective heating degree days (HDD): zone Z1 – South European countries (564 to 2500 HDD), zone Z2 – Central European countries (2501 to 4000 HDD), and zone Z3 – North European countries (4000 to 5823 HDD). Data for these buildings was retrieved from a previous project IMPRO buildings [6] (further details about these buildings are provided in Section 4 of this report).

Two indicators were considered: Global Warming Potential (GWP) and Primary Energy (PE). Moreover, these two impacts are divided into embodied and operational impacts. The latter refer to the impacts due to the consumption of energy for heating and cooling the building during its service life; while the former refer to the impacts due to the production, use and ultimately disposal of the materials.

The results are normalized by the area of each building and per year (taking into account the working life considered for each building). Furthermore, the LCA results are split into embodied impacts and impacts due to the use of energy during the operational stage of the building, operational impacts.

Figure 6. Köppen-Geiger climate classification in Europe [14]



The importance of embodied energy and embodied global warming potential, in relation to the global LCA results, is indicated in Table 2. It is observed that embodied global warming and embodied energy have a higher contribution in climatic zone Z1 than in climatic zone Z3. In the latter, the importance of the impacts due to the use of energy are naturally higher.

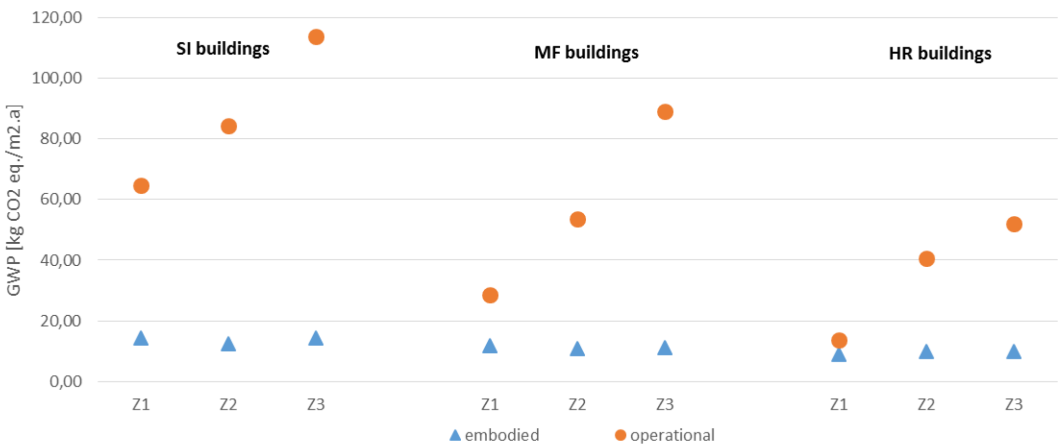
Table 2. Share of embodied GWP and embodied PE in relation to global impacts

Climatic area		Z1			Z2			Z3	
Building type	SI	MF	HR	SI	MF	HR	SI	MF	HR
Embodied Global warming	24%	31%	40%	10%	15%	19%	10%	12%	16%
Embodied energy	16%	23%	27%	12%	12%	14%	7%	8%	10%

The comparison between the different values is better illustrated in Figure 7 for the impact category of global warming potential. It is observed that the values of embodied global warming have not a significant variation within each climatic area and even with the building type, although a slight increase is observed from climate area Z1 to Z3.

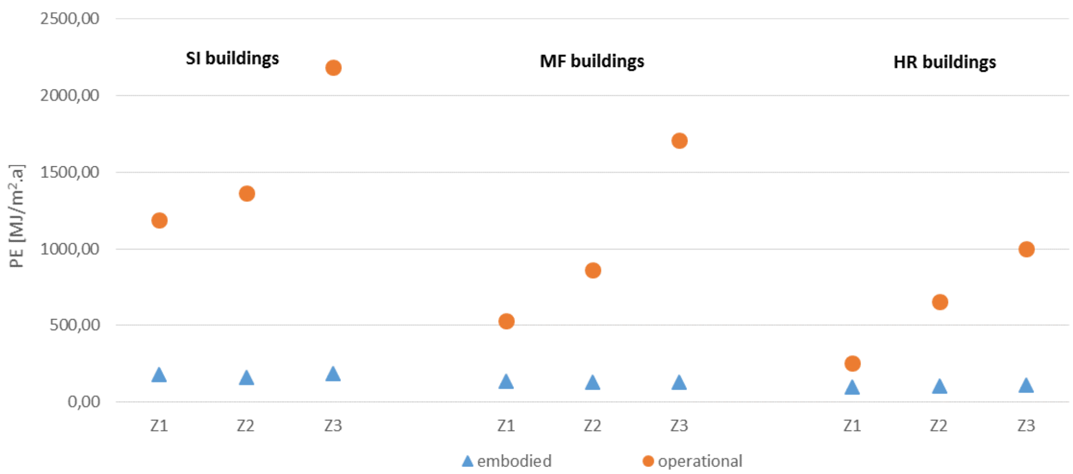
On the other hand, the values for the operational carbon have a much higher variation within each climatic area, increasing from climatic area Z1 to Z3. In terms of building type, the values for high-rise buildings are lower than multi-family buildings and much lower than single-family houses.

Figure 7. Mean embodied and operational GWP values (in *kg CO_2 eq./m^2.yr*) for all buildings in the three climatic areas



In relation to primary energy, the comparison between the different values is illustrated in Figure 8. Likewise, it is observed that the values of embodied primary energy have not a significant variation within each climatic area and building type, although slightly higher values are found for climatic area Z3. On the other hand, the values for the operational primary energy have a much higher variation within each climatic area, increasing from Z1 to Z3, and building type.

Figure 8. PE values (in $MJ/m^2.yr$) for all building



As observed from the previous example, the climatic region where the building is located has a huge influence in the operational energy of the building and related impacts. Thus, benchmarks for the global performance of buildings should not neglect this important factor.

However, its influence in terms of embodied impacts is reduced, particularly when only the structural system of the building is considered, which is the case in this project.

2.3.4 Vulnerability to climatic changes

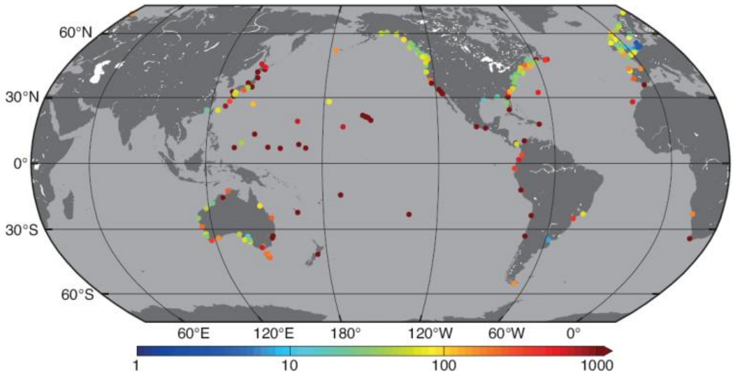
Climate changes due to the increased anthropogenic greenhouse gas concentrations in the atmosphere will have significant detrimental effects on buildings and infrastructures.

Moreover, today we have to face a sad reality: most aspects of climate change will persist for many centuries even if CO_2 emissions are stopped [15]. Thus, the adaptation of existing buildings and the design of new buildings, mainly in vulnerable areas, has to tackle higher structural and functional demands due to the consequences of climate change, both extreme events and longer-term processes.

For instance, coastal areas are the most vulnerable locations in the case of sea rise, which is one of major and inevitable consequences of climate change according to the 5th report from the IPCC [15]. It is estimated that the level of the sea will rise by an average value of 0.52 m by the end of this century compared with values of today. Although inundations of low-lying areas by the sea rise, over the 21st century, will be a problem, the most devastating impacts are likely to be associated with changes in extreme sea levels resulting from storms, which are expected to become more intense. The estimated multiplication factor, by which the frequency of flooding events increases for a mean sea level rise of 0.5 m, is represented in Figure 9 [15].

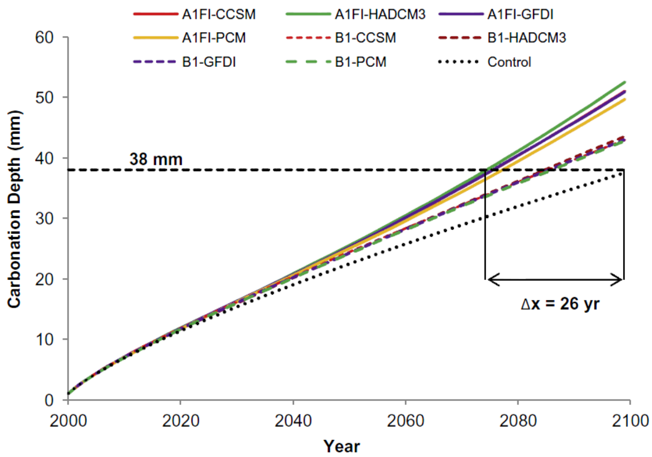
On the other side, variations in temperature, humidity and CO_2 concentrations may affect directly or indirectly the long-term performance of concrete structures due to enhanced corrosion induced by increased rates of carbonation and chlorination.

Figure 9. Frequency of flooding events for a mean sea level rise of 0.5 m [15]



Some studies available in the literature suggest that, in most vulnerable locations, concrete structures designed according to current regulations will experience carbonation and chlorination depths that are beyond the cover thickness currently recommended by the codes, thus requiring extensive repairs [16][17][18], as illustrated in Figure 10, for a concrete building located in the metropolitan area of Boston [18].

Figure 10. Estimated carbonation depth for a building in Boston constructed in 2000, according to different climatic scenarios (extracted from [18])



However, currently, there is a high level of uncertainties in future climatic scenarios and the relation between the effects of climate change on the degradation of materials and structures is hard to be established with an acceptable level of reliability [19][20]. Therefore, in this project, the quantification of benchmarks will not take into account the vulnerability of buildings to climatic changes. Nevertheless, it is highlighted that this may become a differentiate factor for benchmarks in the near future.

3 Benchmarks from literature review

Before the attempt to establish a preliminary set of reference values, an extensive literature review was carried out, in order to collect reference values for the environmental assessment of buildings.

Although values are available in the literature for different building typologies, in the following, the focus will be on residential and office buildings.

The values are organized according to the following:

- Reference values for embodied impacts and global impacts;
- Reference values according to different building typologies;
- Reference values according to different structural systems.

3.1 Embodied *vs*. global values

Most reference values found in the literature are referring to the operational stage of buildings, thus referring to the energy needed for heating and cooling the building, over its service life. In a review made by Peng et al. [21], based in more than 100 buildings across different countries, the life cycle energy consumption of residential and commercial buildings is in the range of 40-400 kwh/m^2.yr and 120 - 550 kwh/m^2.yr, respectively. For life cycle CO_2 emissions the values are 50 kg CO_2 eq./m^2.yr and 30 - 230 kg CO_2 eq./m^2.yr, respectively for residential and commercial buildings. The share of embodied energy and embodied CO_2 emissions in these global values, is up to 80% for residential buildings and about 20% for commercial buildings.

In another study [22], the assessment of buildings with different typologies was carried out for different indicators and for two life spans: 50 years and 100 years. In this study, the values are normalized by the net floor area of each building. In terms of the global performance of buildings, the life cycle primary energy is in the range of 170-380 kwh/m^2.yr, with a median value of 210 kwh/m^2.yr, for a life span of 50 years. For a life span of 100 years, the median value is reduced to 200 kwh/m^2.yr. For life cycle GHG emissions and a life span of 50 years, the range is 15-23.5 kg CO_2 eq./m^2.yr, with a median value of 19 kg CO_2 eq./m^2.yr. In this case, for a life span of 100 years, the median value is reduced to 10.5 kg CO_2 eq./m^2.yr. The shares of embodied impacts are about 25% for primary energy and about 55% for GHG emissions.

The share of embodied impacts in relation to life cycle impacts, depends not only of the type of building but also on the options taken for the design. For instance, in terms of energy consumption, buildings that are designed to be energy efficient tend to have a higher share of embodied energy in relation to the whole energy. In a review performed by Sartori and Hestnes [23], the share of embodied energy in conventional buildings was in the range of 2% - 38%, while, in 'low-energy' buildings the share ranged between 9% - 46%.

3.2 Buildings with different typologies

As already indicated in the previous sub-section, the building typology has a strong influence in the life cycle performance of the building and consequently, in the reference values obtained for each type of building.

In the following paragraphs, reference values are provided for different building typologies.

3.2.1 French survey from HQE

In a statistical analysis made by the French Association HQE and *Centre Scientifique et Technique du batiment* (CSTB) [22], the performance of 63 buildings was carried out based on an approach developed by HQE for the assessment of the environmental performance buildings.

Three types of buildings were considered: individual houses (MI), collective buildings (IC) and office buildings (BB). The analysis took into account two time frames: 50 and 100 years.

The results for Primary Energy and Climate Change are indicated in Table 3, taking into account the global performance of the buildings (including the values related to operational energy consumption). The values in bold are the median values and the minimum and maximum values correspond to the 1st and 3rd quartiles, respectively. In all cases, the values are normalized by the net floor area.

Table 3. Global results of life cycle analysis for a time period of 50 years [22]

Type of building	Primary energy (kwh/m^2.yr)	Climate change (kg CO_2 eq./ m^2.yr)
BB	170-**300**-380	17-**20**-25
IC	205-**225**-240	21.5-**23**-26
MI	170-**180**-210	11-**15**-18

Office buildings have a higher value for primary energy in relation to other buildings; although for climate change, the value for collective buildings is slightly higher. In all cases, the range of values is significant.

Taking into account only the building component of 'construction products and equipment', the results are indicated in Table 4. In this case, office buildings present the higher values, both for primary energy and climate change

Table 4. Results of life cycle analysis for 'Construction products and equipment', for a time period of 50 years [22]

Type of building	Primary energy (kwh/m^2.yr)	Climate change (kg CO_2 eq./ m^2.yr)
BB	53-**62.8**-78	11-**13**-16
IC	45-**49.7**-60	8.5-**10.5**-12
MI	44-**51.4**-58	6-**8.4**-10

The building component of 'Construction products and equipment' was further divided into: (i) main construction works, which included accesses and general infrastructure (Lot 1), foundations of sub-structure (Lot 2) and superstructure (Lot 3); (ii) secondary construction works and (iii) equipment.

Focussing on the structural system (lots 2 and 3), the results are indicated in Table 5.

Table 5. Results of life cycle analysis for the structural system, for a time period of 50 years

Type of building		Primary energy (kwh/m^2.yr)	Climate change (kg CO_2 eq./ m^2.yr)
BB	Lot 2	7.09	2.66
	Lot 3	10.30	3.88
IC	Lot 2	4.42	1.41
	Lot 3	10.96	3.87
MI	Lot 2	3.28	1.04
	Lot 3	7.99	2.00

The weight of the performance of the structural system in relation to 'construction products and equipment' and to the complete the building, are highlighted in Table 6, for each building typology.

In relation to the performance of the global building, the weight of the structural system is below 10% for the environmental category of 'primary energy', for all buildings, but it is higher than 20% for 'climatic change' for IC and MI and higher than 30% for BB.

Naturally, the importance of the structural system to the component 'Construction products and equipment' increases. In this case, for primary energy, IC has the highest contribution with 31% and MI the lowest with 22%. In relation to 'climatic change', the minimum and maximum shares are 36% for MI and 50% for the other typologies.

Table 6. Importance of the structure (lots 2 and 3) in relation to 'construction products and equipment' and global building [22]

	Primary energy		Climatic change	
	construction products and equipment	global building	construction products and equipment	global building
BB	28%	6%	50%	33%
IC	31%	7%	50%	23%
MI	22%	6%	36%	20%

The results indicated above are referring to a life span of 50 years. However, the conclusions for a life span of 100 years are similar to the ones obtained for the time span of 50 years, with slight reductions found for the global performance of the building: about -5% for 'primary energy' and about -15% for 'climatic change'.

The influence of different construction systems is indicated in Table 7, taking into account the environmental indicator of 'primary energy – non-renewable energy' and the building component of 'construction products and equipment'.

Table 7. Results for different construction systems – non-renewable energy (in kwh/m^2.yr) [22]

	MI	IC	BB
Clay brick	32-**36**-40	34-**36**-38	-
Concrete Block	37-**41**-53	38-**41**-42	26-**34**-42.5
Cellular concrete	36-**41**-45	-	-
Reinforced concrete	-	39-**40**-46	40-**49**-64
Wood/concrete frame	28-**32**-39	37-**38**-39	-
Steel/concrete frame	-	-	43-**44**-53

However, when only the building component of 'construction products and equipment' is considered, no significant differences were found between the construction systems.

3.2.2 Annex 57 (International Energy Agency)

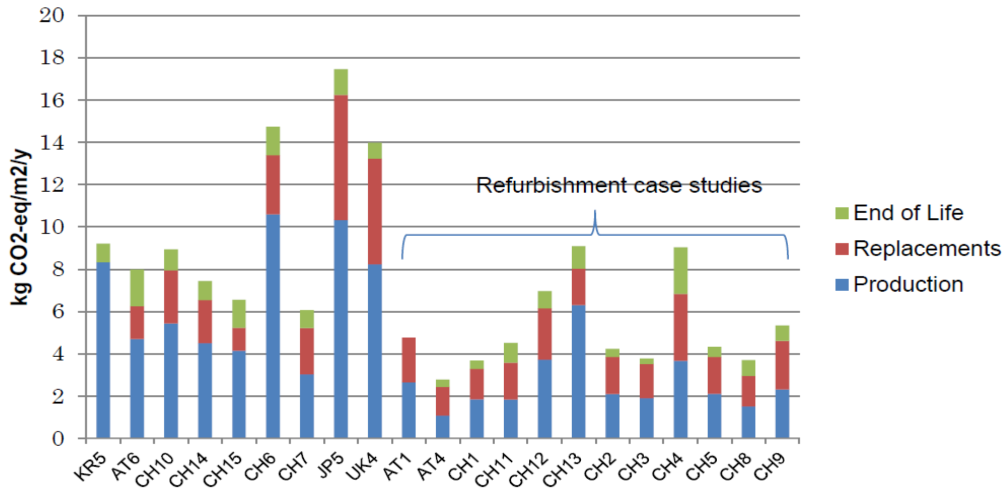
In a different survey, this time performed by the International Energy Agency, about 80 buildings from different countries, were evaluated in terms of the embodied energy and embodied CO_2 [24].

Contrary to the previous survey, the results of this survey are not truly comparable as most of the collected case studies were analysed based on different methodologies, databases and system settings, thus leading to some inconsistencies in the results.

The results of the case studies are indicated in Figure 11 and Figure 12, for embodied carbon and embodied energy, respectively. It is noticed that some of the case studies are referring to refurbishment. The scope of the analysis included production (Modules A1-A3), replacements over the service life of the building (Module B4) and end-of-life (Modules C3-C4).

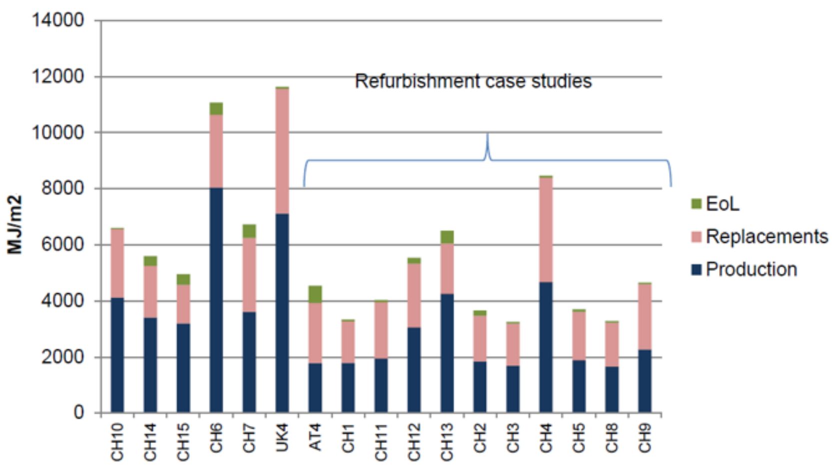
In relation to embodied carbon, the production stage is dominant for all case studies referring to new buildings; in the case of refurbishment, the contribution of the production stage is, in some cases, similar to the contribution of the replacements. The contribution of the end-of-life stage varies from 5% to 25%.

Figure 11. Embodied carbon from Annex 57 case studies (extracted from [24])



The degree to each different methodological options may influence the results of the analysis is observed from Figure 11. In this case, the result of a case study from Japan (JP5) is higher than the remaining cases studies and this is not only due to additional seismic requirements but also because an input-output approach was considered, which usually generates higher results due to wider boundaries.

Figure 12. Embodied energy from Annex 57 case studies (extracted from [24])



In relation to embodied energy (see Figure 12), similar conclusions may be drawn, except in relation to the contribution of the end-of-life stage, which is this case is lower than 10%.

3.2.3 Summary of the values for building typologies

Reference values for embodied carbon and embodied energy, found in the literature for residential and office buildings, are summarized in Table 8. It is noted that some of the sources indicated in the table, provide values also for other building typologies.

As already stressed out, these values are not comparable, not only due to different methodological choices but also due to the lack of information in some of the reviewed sources, which naturally increases the inconsistency of the values. For instance, in many cases the results are normalized by the area of the building but no information is given about the type of area considered (e.g., net floor area - NFA or gross floor area - GFA). Likewise, the scope of the analysis and the building components considered in the analysis are often not clear (e.g., cradle-to-gate - C2Gt or cradle-to-grave - C2G). In cases no information was provided, this is indicated in Table 8 by 'n.a'.

Nevertheless, the aim of the following table is to show the huge variability of the values that are currently found in the literature in relation to residential and office buildings, which do not enable to establish a trend between residential and office buildings.

Table 8. Reference values according to different building typologies

	Sub-type	Area	Scope	Building components	Embodied GWP (kg CO_2 eq./m^2)	Embodied energy (MJ/m^2)	Ref.
Residential buildings	MF	n.a.	C2G	Building materials	435-1162	2817-7837	[21]
	SI	n.a.	C2Gt	Structure	243-**267**-286	-	[25]
	MF_l	n.a.	C2Gt	Structure	131-**159**-202	-	
	MF_m	n.a.	C2Gt	Structure	150-**168**-397	-	
	MF_h	n.a.	C2Gt	Structure	206-**257**-342	-	
	MF	NFA	C2Gt	Building materials	164-173	-	[26]
	MF	NFA	C2Gt	Building materials and repair materials	176-186	-	
	DA	GFA	C2Gt	Building materials	1158	-	[27]
	MF	GFA	C2Gt	Building materials	704	-	[27]
	SI	n.a.	C2G	Building materials & equipment	-	25-515$^{(*)}$	[28]
	MF	n.a.	C2G	Building materials & equipment	-	79-126$^{(*)}$	[28]
	SI	NFA	C2G	Building materials & equipment	300-**420**-500$^{(**)}$	7920-**9252**-10440$^{(***)}$	[22]
	MF	NFA	C2G	Building materials & equipment	425-**525**-600$^{(**)}$	8100-**8946**-10800$^{(***)}$	[22]
Office buildings	-	n.a.	C2G	Building materials	731-1053	5540-7157	[21]
	-	n.a.	C2Gt	Structure	227-**330**-418	-	[25]
	-	GFA	C2Gt	Building materials	674	-	[27]
	-	n.a.	C2G	Building materials & equipment	-	119-500$^{(*)}$	[28]
	-	n.a.	C2Gt	Building materials & equipment	843-1033	7743-11939	[29]
	-	NFA	C2G	Building materials & equipment	550-**650**-800$^{(**)}$	9540-**11304**-14040$^{(***)}$	[22]

$^{(*)}$ values are given in MJ/m^2.yr
$^{(**)}$ values were multiplied by 50 years
$^{(***)}$ values were converted to MJ and multiplied by 50 years

3.3 Buildings with different structural systems

The importance of the structural system of a building in relation to the global environmental performance of a building is considered to be small by some authors. However, the weight of the structure accounts for the highest share of the weight of the building, thus contributing to a significant share of impacts [30] and costs [31]. For instance, the structural systems of office buildings may account for 60%-67% of the total embodied energy [32]; while, the embodied carbon of structures may reach shares of 20% to 40% [22][33].

The structural system of a building is the main focus of the research project *EFIResources* and therefore, this sub-section summarizes reference values for embodied carbon and embodied energy found in the literature for different structural systems. These values are provided in Table 9. Likewise, emphasis is given only to residential and office buildings.

It is noticed once again that the following values are not truly comparable as they are based on different methodological choices and, in some cases, information about important parameters is omitted in the reviewed sources.

Table 9. Reference values according to different structural systems

	Building type	Area	Scope	Building components	Embodied GWP (kg CO_2 eq./m^2)	Embodied energy (MJ/m^2)	Ref.
Steel	various	n.a.	C2Gt	Structure	229-**385**-534	-	[25]
	OF	GFA	C2Gt	Structure + foundation	473 (*)	4869	[29]
	n.a.	GFA	C2G	Structure	152-209	-	[34]
	RE	n.a.	C2G	Building materials	241	-	[35]
	RE	n.a.	n.a.	Building materials	278	-	[36]
	RE	GFA	C2Gt	Building materials	354	1800	[37]
	OF	GFA	C2Gt	Structure	530-550 (*)	5595-5770	[31]
Reinforced Concrete	various	n.a.	C2Gt	Structure	277-**361**-434	-	[25]
	OF	GFA	C2Gt	Structure + foundation	497 (*)	4366	[29]
	OF	GFA	C2G	All building materials	491	-	[38]
	n.a.	GFA	C2G	Structure	159-242	-	[34]
	OF	GFA	C2Gt	Structure	390-410 (*)	4090-4321	[31]
	RE	n.a.	C2G	Building materials	332	-	[35]
	RE	n.a.	n.a.	Building materials	338	-	[36]
	RE	GFA	C2Gt	Building materials	433	2602	[37]
	OF	NFA	C2Gt	Building materials + equipment	-	7200-**8820**-11520 (**)	[22]
	RE	NFA	C2Gt	Building materials + equipment	-	7020-**7200**-8280 (**)	[22]
Wood	various	n.a.	C2Gt	Structure	174-**244**-293	-	[25]
	RE	n.a.	C2G	Building materials	108	-	[35]
	RE	n.a.	n.a.	Building materials	172	-	[36]
	RE	GFA	C2Gt	Building materials	288	1181	[37]
Masonry	various	n.a.	C2Gt	Structure	243-**265**-281	-	[25]
	RE	NFA	C2Gt	Building materials + equipment	-	6120-**6480**-6840 (**)	[22]
Steel & Concrete	various	n.a.	C2Gt	Structure	245-**381**-523	-	[25]
	OF	GFA	C2Gt	Structure + foundation	744 (*)	7616	[29]
	OF	NFA	C2Gt	Building materials + equipment	-	7740-**7920**-9540 (**)	[22]

(*) Based in I/O
(**) Only non-renewable energy is considered

Table 9 shows a huge variability for each structural system and it is not possible to establish a trend between the different systems. Among the reasons indicated above, the scope of the life cycle analysis is of particular importance for construction materials, as discussed in [2]. The consideration of a cradle-to-gate (C2Gt) analysis or a cradle-to-grave (C2G) analysis has a huge influence for some materials, which obviously leads to inconsistencies in comparative assertions.

To illustrate this, the cradle-to-grave results for some construction materials are indicated in Table 10, from different sources. It is noted that these values are not representative of each material. Furthermore, it is observed that comparisons, at the product level, are meaningless.

As observed from Table 10, for some materials (such is the case of concrete), cradle-to-gate values (Modules A1-A3) are not substantially changed when the complete life cycle is taken into account. However, for other construction products, this is not usually the case.

Taking into account the case of steel reinforcement indicated in Table 10, when only cradle-to-gate values are considered, the production 1 kg of steel leads to 3.20 kg CO_2 eq. However, when the complete life cycle (cradle-to-cradle) is considered than the value of GWP is reduced to 2.21 kg CO_2 eq.

Table 10. Examples of GWP values (in kg CO_2 eq./declared unit) for different construction materials

Material	Declared unit	GWP	A1-A3	C1-C4	D	Total	Source of data
C40 concrete mix	1 kg	-	0.13(a)	0.0043(b)	-0.0053(b)	0.13	(a) GaBi database [39] (b) data from [40]
Steel reinforcing	1 kg	-	3.20	0.0079(*)	-1.00	2.21	EPD reg. no.: S-P-00855 [41]
Softwood timber (sawn)	1 m^3	GWPT	-760	906(**)	-585(**)	-439	EPD reg. no.: S-P-00560 [41]
		GWPF	128	5.59(**)	-586(**)	-452	
		GWPB	-887	900(**)	1.41(**)	14.41	

(*) only Modules C3-C4 were considered
(**) only Module C3 was considered and the end-of-life scenario includes shredding (module C3) and combustion with recovered energy offset against average thermal energy from natural gas (module D)

Similarly, for wood products, the scope of the analysis has a huge influence on the results of the LCA. However, in this case, there is an additional question to be considered: the biogenic carbon sequestration. The carbon that is absorbed from the atmosphere by biomass as it grows is temporarily stored into wood materials, but at the end-of-life stage of these materials, through decomposition or incineration, the carbon emissions that were temporarily stored are released. Therefore, the omission of end-of-life stages in the scope of the analysis could lead to bias results.

Moreover, biogenic carbon should only be considered in Module A1-A3, when the wood is originated from a sustainably managed forest[1], which is the case of the wooden material indicated in Table 10, according to the information provided by the source. In this case, the results for the softwood timber are reported as a total GWP (GWPT), as well as biogenic carbon (GWPB) and fossil carbon (GWPF). In all cases, the values from Modules A1-A3 alone are completely different from the overall values (Modules A1-D).

For a matter of transparency, in the developed model for LCA [2], the environmental category of GWP was divided into GWP including biogenic carbon and GWP excluding biogenic carbon.

[1] A sustainable forest 'is carbon and climate neutral and preserves biodiversity to support fundamental functionalities and ecosystems services on a landscape level' [42]

4 Preliminary set of benchmarks for residential buildings

4.1 Introduction

The preliminary set of benchmarks is based on the assessment of the environmental performance of the case studies included in the project *Environmental Improvement Potentials of Residential Buildings* (IMPRO-Building) [6]. The LCA model used for the assessment of the buildings is fully described in [2].

The goal of the IMPRO-Building project was the analysis of the potential environmental improvements of residential buildings in the EU-25. The project took into account all relevant types of residential buildings, from single-family houses to multi-apartment buildings, including existing and new buildings.

Hence, in the framework of the referred project, data was collected to define relevant building models with enough representativeness of the building stock at the EU-25 level. The buildings were divided into three building types (single-family houses (SI), multi-family buildings (MF) and high-rise buildings (HR)), representing 53%, 37% and 10% of SI, MF and HR buildings, respectively, of the existing EU-25 building stock.

In addition, the buildings cover the three main climate zones in Europe according to heating degree days (HDD): zone Z1 – South European countries (564 to 2500 HDD), zone Z2 – Central European countries (2501 to 4000 HDD), and zone Z3 – North European countries (4000 to 5823 HDD).

Therefore, 72 building models (53 existing buildings and 19 new building types) were considered, as indicated in Table 11. A full description of each building, including the bill of the main materials, is provided in the final report of the *IMPRO* project [6].

Table 11. Number of buildings and types in each zone [6]

	Single-family house		**Multi-family house**		**High-rise building**	
Climatic zones	existing	new	existing	new	existing	new
Zone 1: South European countries	8	3	8	3	2	1
Zone 2: Central European countries	8	3	8	3	2	1
Zone 3: North European countries	7	2	8	2	2	1
TOTAL	31		32		9	

The list of buildings, including the information about the type of structure, is provided in Annex 1 of this report. Following the notation used in the previous project, each building is identified by the following reference: "Zone type (ZX)_Building type (XX)_Number (XXX)". Zone type refers to the three climatic regions: Z1 – southern European countries, Z2 – central European countries and Z3 – northern European countries; while, building type refers to: SI – single-family houses, MF – multi-family houses and HR – high-rise buildings.

4.2 Statistical analysis of LCA results

The methodology that is used to establish the preliminary set of benchmarks ("best" and conventional" values) is based on the statistical evaluation of the results obtained for each European area.

The life cycle environmental assessment of each building is based on the functional equivalent, which includes the type of use of the building, the total gross floor area and a reference period of time [2]. Thus, the result for each indicator is normalized by the area and number of years considered for each building.

In this case, the type of use refers to residential buildings, although a subdivision is made in terms of single family houses (SI), multi-family houses (MF) and high-rise buildings (HR). The reference period is taken as the service life considered for each building in the IMPRO project.

The life cycle analysis of each building is limited to the structural system [2], hence insulation materials and other non-structural elements were not considered in the analysis. The scope of the LCA comprehends Modules A1-A3, Module B4, Modules C1-C4 and Module D.

The analysis was performed for all indicators in Table 1. However, in this report, emphasis is given to two indicators: Global Warming Potential (in kg CO_2 eq./m^2.yr) and Primary Energy (in MJ/m^2.yr). Global Warming Potential is further divided in order to include biogenic carbon (GWP1) and exclude (GWP2).

As previously referred, in the following statistical analysis it is assumed that the conventional practice is given by the median of the values and the best practice given by the first quartile (25%), i.e., the boundary of the 25% lowest values. In the sample of values, no discrepancy values (outliers) where found.

4.2.1 Statistical analysis of European area Z1

The results are represented in Table 12 for European area Z1. The results presented in this table are aggregated over the life cycle of each building.

Table 12. Statistical analysis for life cycle aggregated results [GWP (kg CO_2 eq./m^2.yr) and PE (MJ/m^2.yr)] in Z1

		Mean value	**Median**	Standard deviation	**Quartile 25%**	Quartile 75%
SI	GWP1	7.61	**7.19**	4.16	**5.16**	9.34
	GWP2	9.87	**9.32**	4.81	**8.17**	14.03
	PE	162.12	**154.00**	57.22	**117.62**	205.55
MF	GWP1	7.40	**7.03**	3.31	**4.82**	10.44
	GWP2	8.62	**8.06**	3.89	**5.15**	12.66
	PE	124.58	**112.45**	52.33	**85.26**	168.50
HR	GWP1	7.07	**5.58**	2.94	**4.46**	11.18
	GWP2	7.51	**6.21**	2.68	**5.08**	11.24
	PE	100.86	**82.25**	37.41	**67.27**	153.05

The values obtained for GWP2 are, in general, higher than the values for GWP1 due to the contribution of structural elements in wood.

The lowest values correspond to high-rise buildings and the highest values are for single-family houses.

4.2.2 Statistical analysis of European area Z2

The aggregated results for European area Z2 are represented in Table 13.

Table 13. Statistical analysis for life cycle aggregated results [GWP (kg CO_2 eq./m^2.yr) and PE (MJ/m^2.yr)] in Z2

		Mean value	**Median**	Standard deviation	**Quartile 25%**	Quartile 75%
SI	GWP1	5.39	**7.20**	2.55	**2.53**	7.54
	GWP2	6.77	**7.40**	2.58	**3.94**	9.27
	PE	134.65	**131.83**	20.95	**126.60**	148.61
MF	GWP1	6.46	**5.64**	3.19	**4.67**	7.30
	GWP2	7.28	**7.26**	3.10	**4.79**	9.32
	PE	112.53	**105.25**	41.90	**85.16**	125.36
HR	GWP1	5.55	**5.53**	1.10	**4.22**	6.91
	GWP2	6.17	**6.57**	0.85	**4.98**	6.94
	PE	83.86	**88.89**	11.64	**67.77**	94.92

Likewise, the lowest median values correspond to high-rise buildings and the highest values are for single-family houses.

4.2.3 Statistical analysis of European area Z3

For the European area Z3, the results are represented in Table 14, and also in this case the lowest median values correspond to high-rise buildings and the highest values are for single-family houses

Table 14. Statistical analysis for life cycle aggregated results [GWP (kg CO_2 eq./m^2.yr) and PE (MJ/m^2.yr)] in Z3

		Mean value	**Median**	Standard deviation	**Quartile 25%**	Quartile 75%
SI	GWP1	7.00	**7.88**	4.18	**1.91**	10.67
	GWP2	9.17	**8.94**	4.23	**4.53**	13.84
	PE	180.00	**133.89**	66.32	**124.95**	246.23
MF	GWP1	6.64	**5.71**	4.62	**3.74**	10.57
	GWP2	7.69	**8.07**	4.49	**4.64**	11.12
	PE	124.82	**116.86**	50.71	**79.75**	175.95
HR	GWP1	5.55	**5.53**	1.11	**4.19**	6.91
	GWP2	6.17	**6.57**	0.85	**4.99**	6.94
	PE	84.36	**88.91**	10.97	**69.24**	94.93

4.2.4 Statistical analysis for all areas

The previous results were aggregated over the complete life cycle of the buildings. In Figure 13 to Figure 15, the results are provided for the results of Modules A1-A3 and for the corresponding aggregated results, and for each European area.

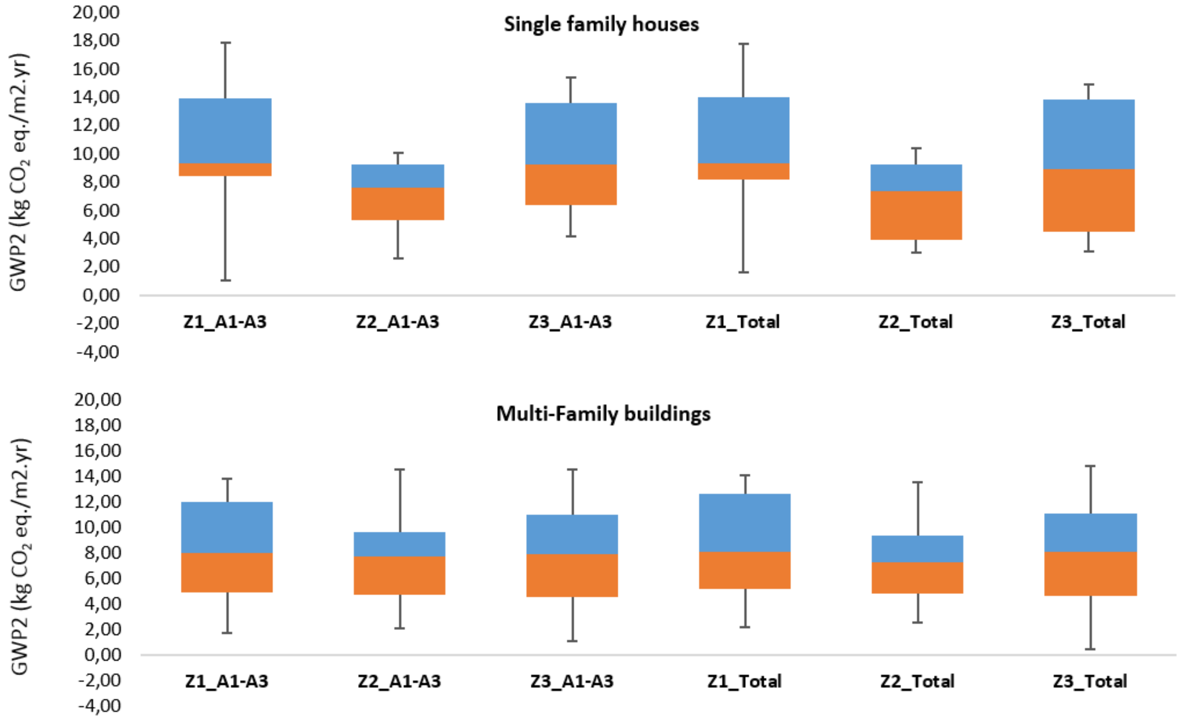
The results for GWP1 are indicated in Figure 13. It is observed that, in all three areas, in terms of median values, the results for Modules A1-A3 and respective aggregated results are very close, both for single houses and multi-family buildings.

The scatter of values found for each area is not related to the climatic area but with the different types of structures in each area.

Figure 13. GWP1 (*kg CO_2 eq./m^2.yr*) for single family houses (SI) and multi-family buildings (MF)

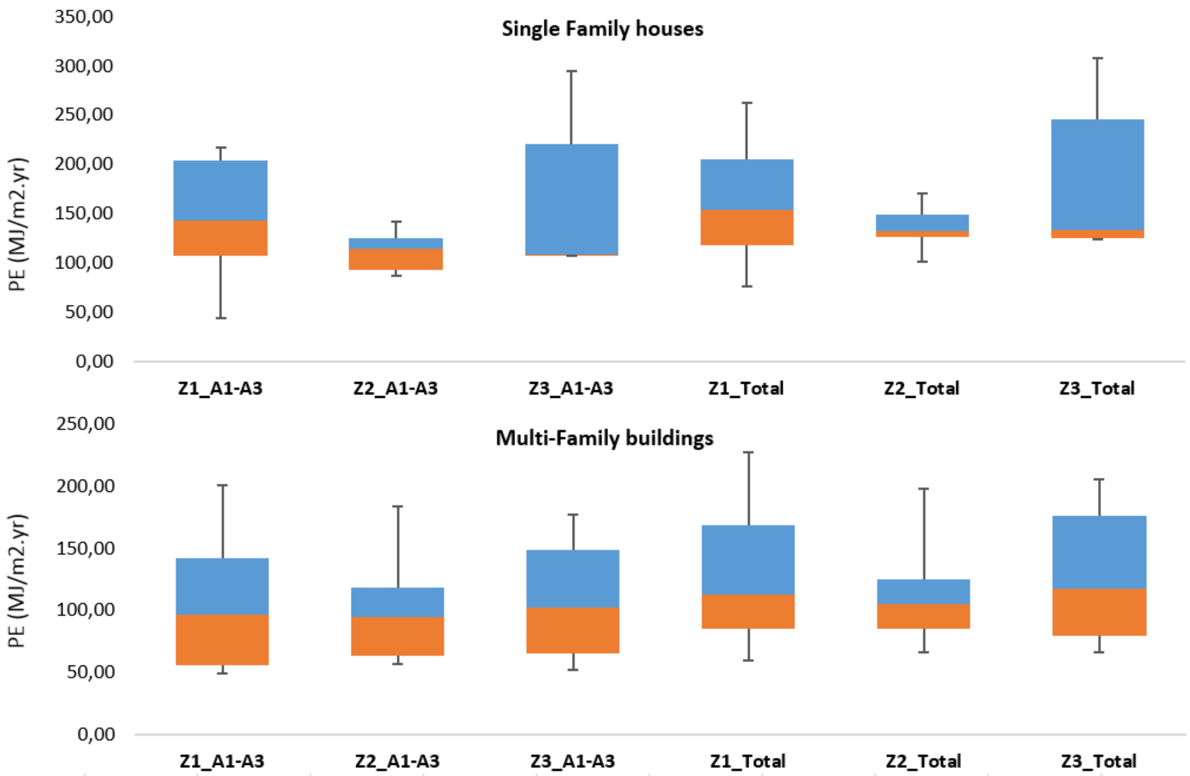
The results for GWP2 are indicated in Figure 14. In this case, for single family houses, the median values for area Z2 are slightly lower than the other 2 areas, but again this due to the different types of structures in the 3 areas.

Figure 14. GWP2 (*kg CO_2 eq./m^2.yr*) for single family houses (SI) and multi-family buildings (MF)



Finally, for PE, the results of Modules A1-A3 and respective aggregated results are indicated in Figure 15.

Figure 15. PE (*MJ/m^2.yr*) for single family houses (SI) and multi-family buildings (MF)



Likewise, there are no significant differences in the results, particularly in relation to multi-family buildings, in terms of median values. For single family houses, the scatter of results is higher and this trend is also noticeable for the previous indicators.

Another conclusion from Figure 13 to Figure 15 is that, in all cases, Modules A1-A3 have a dominant contribution towards the respective aggregated result.

4.2.5 Statistical analysis for all building types

Taking into account the aggregated life cycle result from the three climatic areas, the results for each building type are indicated in Table 15.

Table 15. Statistical analysis for each building type [GWP (kg CO_2 eq./m^2.yr) and PE (MJ/m^2.yr)]

		Mean value	**Median**	Standard deviation	**Quartile 25%**	Quartile 75%
SI	GWP1	6.65	**7.22**	3.80	**2.53**	8.71
	GWP2	8.57	**8.94**	4.20	**5.01**	11.27
	PE	157.56	**139.25**	54.17	**124.19**	186.18
MF	GWP1	6.84	**6.30**	3.76	**4.88**	9.94
	GWP2	7.87	**7.32**	3.89	**5.37**	10.75
	PE	120.51	**105.60**	48.80	**84.50**	159.77
HR	GWP1	6.06	**5.53**	2.05	**4.34**	6.91
	GWP2	6.61	**6.57**	1.81	**5.03**	6.94
	PE	89.69	**88.89**	24.78	**68.51**	94.93

Both in terms of median values, taken as 'conventional practices' and lower quartile values, considered as 'best practices', single family houses have the higher values, followed by multi-family buildings and high-rise buildings. The values obtained for GWP1 are slightly biased due to the higher contribution of wooden structural elements.

Finally, taking into account only Modules A1-A3, the median, lower and upper quartiles, and minimum and maximum values are illustrated in Figure 16 and Figure 17, for GWP and PE, respectively.

Figure 16. GWP1 and GWP2 (in *kg CO_2 eq./m^2.yr*) for all types of buildings (Modules A1-A3)

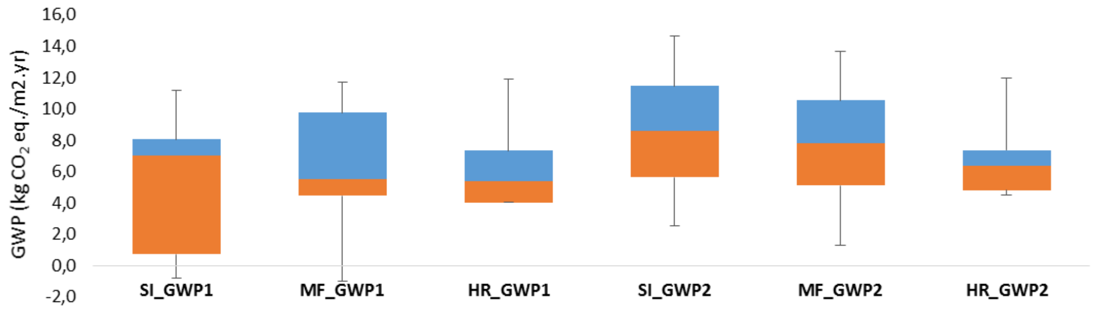
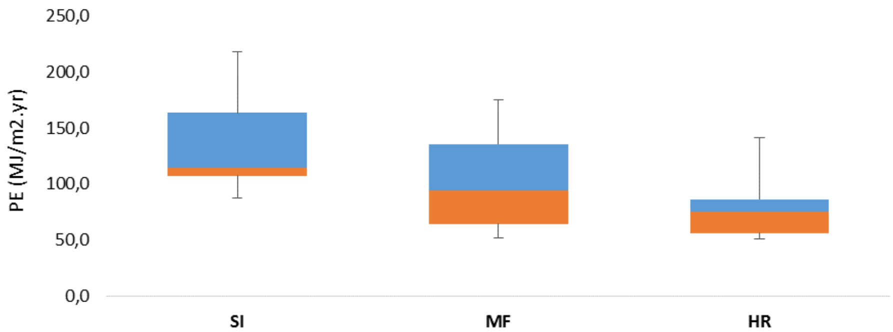


Figure 17. PE (in *MJ/m^2.yr*) for all types of buildings (Modules A1-A3)



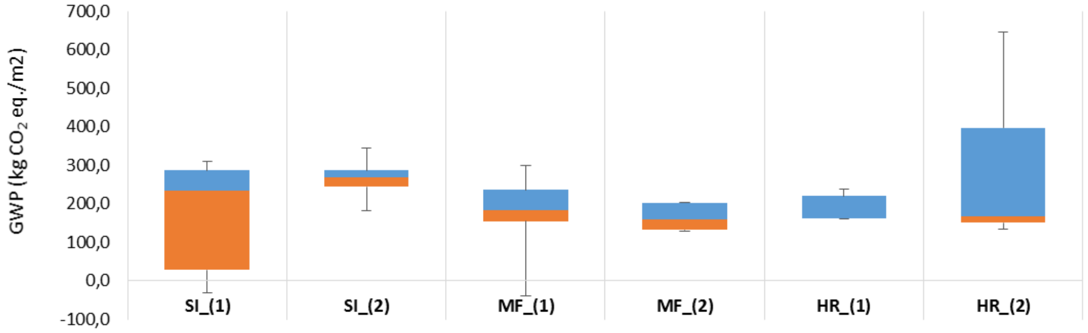
As Modules A1-A3 have a dominant contribution towards the aggregated result, the trend in Figure 16 and Figure 17 is similar to the one observed in Table 15.

4.3 Comparison with available benchmarks

In this section, an attempt is made to compare the values quantified in the previous sub-section to similar values available in the literature. However, as previously referred, the importance of this comparison is only limited since different scopes and assumptions on the respective calculations and different data lead to different results. Therefore, the values are not easily comparable. The main goal of this comparison was simply to understand how the reference values obtained in this chapter are positioned in the range of values available in the literature.

In the first comparison, the results of the analysis are compared with the values available in the database deQo [25]. The comparison is presented in Figure 18 for the impact category of GWP including biogenic carbon, considering only the results from Modules A1-A3.

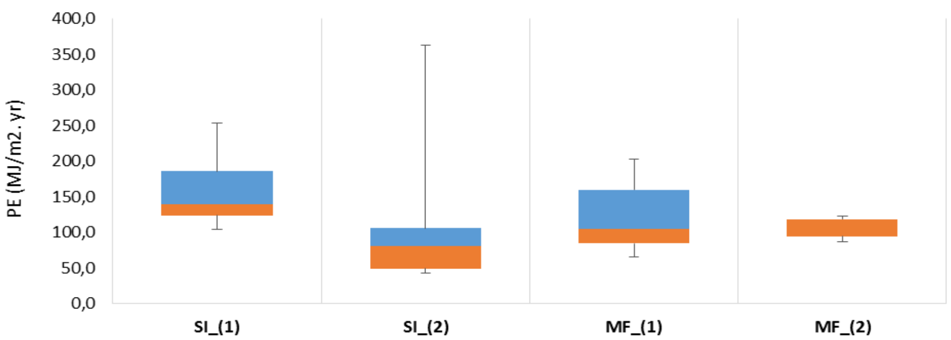
Figure 18. Comparison of benchmarks for GWP (*kg CO_2 eq./m²*)



In terms of the median values, only slight variations are found, about 15% for single-family houses and multi-family houses; while for high-rise building the variation is lower than 5%. In terms of the lower quartile, the values are also quite similar, except for single-family houses. However, there is a huge variation in terms of the range of values for the two groups of results.

In relation to PE, the comparison is made with results from a literature review [28]. For the impact category of PE, the comparison in represented in Figure 19. In this case, life cycle aggregated results are used in the comparison.

Figure 19. Comparison of benchmarks for PE (*MJ/m².yr*)



In this case, a higher variation is found for the median value of single-family houses, about 40%; while for multi-family houses, the variation is much lower, close to 12%. Likewise, there is a huge variation in terms of the range of values for the two groups of results.

5 Conclusions

The research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, aims to support European policies related to the efficient use of resources in construction and its major goal is the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings in the stage of design.

In the proposed approach for sustainability design, the performance of a building, focussing on resource use, is benchmarked against standard and/or best practices. Therefore, the main goal on the development of benchmarks is to provide a consistent and transparent yardstick for the assessment of the environmental performance of buildings, striving towards an effective reduction of the use of resources and relative environmental impacts in the building sector

The adopted framework for the development of benchmarks is based on a graduated approach, starting on a simple basis and being refined and increasing in complexity over time, as data collection on buildings and relative processes will become more complete and precise.

A preliminary set of reference values for residential buildings was established based on the assessment of the environmental performance of 76 case studies provided by a previous research project. These values are based on data referring to representative buildings in the EU and may be considered to be representative of the existing residential building stock in Europe. The values were compared with values from other sources in the literature and, in terms of median values, a good agreement was found. It is observed that the relevance of this comparison is only limited due to the reasons explained in the text.

In the follow-up of this project, a database is foreseen for the collection of building data, which will enable to continuously update the values that will be provided by the end of the current project, thus increasing the accuracy of the values and the reliability of the approach over time.

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List of abbreviations and definitions

$ADP_{elements}$	Abiotic Resource Depletion Potential for elements
$ADP_{fossil\ fuels}$	Abiotic Resource Depletion Potential of fossil fuels
AP	Acidification potential
BoM	Bill of Materials
C2G	Cradle-to-grave
C2Gt	Cradle-to-gate
EDP	Environmental Product Declaration
EP	Eutrophication potential
FW	Use of net fresh water
GFA	Gross Floor Area
GWP	Global Warming Potential
GWP1	Global Warming Potential including biogenic carbon
GWP2	Global Warming Potential excluding biogenic carbon
HR	High Rise buildings
HWD	Hazardous waste disposed
LCA	Life Cycle Analysis/Assessment
MF	Multi-Family buildings
NFA	Net floor area
NHWD	Non-hazardous waste disposed
ODP	Depletion potential of the stratospheric ozone layer
PE	Primary Energy
PEF	Product Environmental Footprint
PENRM	Non-renewable primary energy resources used as raw materials
PENRT	Total use of non-renewable primary energy resources
PERM	Primary energy resources used as raw materials
PERT	Total use of renewable primary energy resources
POCP	Formation potential of tropospheric ozone photochemical oxidants
RWD	Radioactive waste disposed
SI	Single family houses

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Annex 1. List of buildings used in the preliminary set of benchmarks

Table 16. Description of buildings from IMPRO project [6]

	Notation	Description of Building Construction System
1	Z1_SI_001	Brick masonry with wooden flooring
2	Z1_SI_002	Limestone/fieldstone masonry with wooden flooring
3	Z1_SI_003	Limestone/fieldstone masonry, wooden flooring, flat roof
4	Z1_SI_004	Brick masonry, hollow brick flooring, pitched roof
5	Z1_SI_005	Brick cavity wall, reinforced concrete flooring, pitched roof 20°
6	Z1_SI_005(*)	Brick cavity wall, reinforced concrete flooring, pitched roof 20° with ins. (new building)
7	Z1_SI_006	Brick cavity wall, reinforced concrete flooring, flat roof
8	Z1_SI_006(*)	Brick cavity wall, reinforced concrete flooring, flat roof with insulation (new building)
9	Z1_SI_007	Brick masonry insulated, reinforced concrete flooring, pitched roof 20° with insulation
10	Z1_SI_007(*)	Brick masonry insulated, reinforced concrete flooring, pitched roof 20° (new building)
11	Z1_SI_008	Wooden frame with stone filler, reinforced concrete flooring, pitched roof
12	Z1_MF_001	Brick masonry with wooden flooring
13	Z1_ MF _002	Limestone/fieldstone masonry with wooden flooring
14	Z1_ MF _003	Brick cavity wall, reinforced concrete flooring, pitched roof 20°
15	Z1_ MF _004	Breeze concrete, reinforced concrete flooring, pitched roof
16	Z1_MF_004(*)	Breeze concrete, reinforced concrete flooring, pitched roof with insulation (new building)
17	Z1_ MF_005	Concrete wall, reinforced concrete flooring, flat roof
18	Z1_ MF_006	Brick cavity wall insulated, reinforced concrete flooring, flat roof
19	Z1_MF_006(*)	Brick cavity wall ins., reinforced concrete flooring, flat roof with ins. (new building)
20	Z1_MF_007	Concrete wall, reinforced concrete flooring, flat roof
21	Z1_MF_008	Brick cavity wall insulated, reinforced concrete flooring, flat roof
22	Z1_MF_008(*)	Brick cavity wall ins., reinforced concrete flooring, flat roof with ins. (new building)
23	Z1_HR_001	Brick cavity wall insulated, reinforced concrete flooring, flat roof
24	Z1_HR_001(*)	Brick cavity wall ins., reinforced concrete flooring, flat roof with ins. (new building)
25	Z1_HR_002	Concrete wall, reinforced concrete flooring, flat roof
26	Z2_SI_001	Brick masonry with wooden flooring and pitched roof
27	Z2_SI_002	Rubble masonry with wooden flooring and pitched roof
28	Z2_SI_003	Wooden frame with stone filler, reinforced concrete flooring, pitched roof
29	Z2_SI_004	Brick masonry, hollow brick flooring, pitched roof
30	Z2_SI_005	Brick wall, reinforced concrete flooring, pitched roof
31	Z2_SI_006	Brick wall, reinforced concrete flooring, pitched roof

32	Z2_SI_006	Brick wall, reinforced concrete flooring, pitched roof with insulation (new building)
33	Z2_SI_007	Sand lime wall, reinforced concrete flooring, pitched roof
34	Z2_SI_007(*)	Sand lime wall, reinforced concrete flooring, pitched roof with ins. (new building)
35	Z2_SI_008	Wooden frame insulated, wooden flooring, pitched roof
36	Z2_SI_008	Wooden frame insulated, wooden flooring, pitched roof with insulation (new building)
37	Z2_MF_001	Brick masonry with wooden flooring
38	Z2_MF_002	Rubble stone masonry with wooden flooring
39	Z2_MF_003	Wooden frame with stone filler, wooden flooring, pitched roof
40	Z2_MF_004	Brick masonry, reinforced concrete flooring, pitched roof
41	Z2_MF_005	Breeze concrete insulated, reinforced concrete flooring, pitched roof
42	Z2_MF_005(*)	Breeze concrete ins., reinforced concrete flooring, pitched roof with ins. (new building)
43	Z2_MF_006	Brick masonry insulated, reinforced concrete flooring, pitched roof
44	Z2_MF_006(*)	Brick masonry ins., reinforced concrete flooring, pitched roof with ins. (new building)
45	Z2_MF_007	Sand lime wall insulated, reinforced concrete flooring, pitched roof
46	Z2_MF_007(*)	Sand lime wall ins., reinforced concrete flooring, pitched roof with ins. (new building)
47	Z2_ MF_008	Concrete wall, reinforced concrete flooring, pitched roof
48	Z2_HR_001	Concrete wall, reinforced concrete flooring, flat roof
49	Z2_HR_002	Brick cavity wall insulated, reinforced concrete flooring, flat roof
50	Z2_HR_002(*)	Brick cavity wall ins., reinforced concrete flooring, flat roof with ins. (new building)
51	Z3_SI_001	Brick masonry with wooden flooring and pitched roof
52	Z3_SI_002	Brick wall, reinforced concrete flooring, pitched roof
53	Z3_SI_003	Wooden wall, wooden flooring, pitched roof
54	Z3_SI_004	Wooden wall and brick facade, reinforced concrete flooring, pitched roof
55	Z3_SI_005	Breeze concrete wall, breeze concrete block flooring, pitched roof
56	Z3_SI_006	Brick wall, reinforced concrete flooring, pitched roof
57	Z3_SI_006(*)	Brick wall, reinforced concrete flooring, pitched roof with insulation (new building)
58	Z3_SI_007	Wooden frame insulated, wooden flooring, pitched roof
59	Z3_SI_007(*)	Wooden frame insulated, wooden flooring, pitched roof with insulation (new building)
60	Z3_MF_001	Brick masonry with wooden flooring
61	Z3_MF_002	Breeze concrete insulated, reinforced concrete flooring, pitched roof
62	Z3_MF_003	Wooden wall brick façade, reinforced concrete flooring, pitched roof
63	Z3_MF_004	Brick masonry, reinforced concrete flooring, pitched roof
64	Z3_MF_005	Breeze and reinforced concrete wall, reinforced concrete flooring, pitched roof

65	Z3_MF_006	Wooden wall insulated, wooden flooring, pitched roof
66	Z3_MF_006(*)	Wooden wall insulated, wooden flooring, pitched roof with insulation (new building)
67	Z3_MF_007	Brick masonry insulated, reinforced concrete flooring, pitched roof
68	Z3_MF_007(*)	Brick masonry insulated, reinforced concrete flooring, pitched roof with ins. (new building)
69	Z3_MF_008	Concrete wall insulated, reinforced concrete flooring, flat roof
70	Z3_HR_001	Concrete wall, reinforced concrete flooring, flat roof
71	Z3_HR_002	Brick cavity wall insulated, reinforced concrete flooring, flat roof
72	Z3_HR_002(*)	Brick cavity wall insulated, reinforced concrete flooring, flat roof with ins. (new building)

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