Energy & Buildings 347 (2025) 116357

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Measuring the impact of holistic energy retrofit strategies: Life cycle assessment aligned with level(s)

Anna Dalla Valle, Hashem Amini Toosi, Fabrizio Leonforte *, Claudio Del Pero, Monica Lavagna, Andrea Campioli, Niccolò Aste

Department of Architecture, Built Environment, and Construction Engineering (DABC), Politecnico di Milano, Milano, Italy

ARTICLE INFO

Keywords:
Life cycle assessment
Level(s)
Smart building technology
Deep Energy retrofit
Global Warming Potential

ABSTRACT

The building sector plays a significant role in global energy consumption and greenhouse gas emissions, prompting urgent action to align with climate-neutral objectives. Consistently, the European Union (EU) has set ambitious targets for reducing emissions and increasing energy efficiency in buildings, stressing the need for balanced strategies that go beyond operational energy performance and address life cycle impacts. To this end, holistic sustainability assessment methods, such as Life Cycle Assessment (LCA), and tools, like Green Building Rating Systems (GBRSs) and Level(s), are of utmost importance towards measuring and improving the sustainability performance of buildings. This paper applies building-level LCA, in compliance with Level(s) framework, to a real-case building retrofit under the HEART H2020 project. In particular, the retrofitting involves the integration of smart technologies, including smart fan coils and DHW boilers, thermal energy storages, DC heat pumps, photovoltaic tiles, a multifunctional converter, modular façade thermal insulation panels and components to retrofit existing windws. Here, a specific methodological approach is adopted, since the environmental impacts of each technology are scaled to one year of service, independently of any predefined reference study period. LCA results demonstrate significant improvements in the environmental performance pre- and post-retrofit: the total Global Warming Potential (GWP) is reduced by 73%, with a 90% reduction in energy-related GWP impacts. These achievements highlight the effectiveness of the adopted technologies in lowering both embodied and operational impacts. Overall, the findings contribute to the holistic understanding of sustainability in building energy retrofit projects and serves as a reference for future research in the field.

1. Introduction

The significant share of the building sector in final energy consumption and greenhouse gas emissions indicates the necessity of taking immediate actions in accordance with climate-neutral action plans [1,2]. The building industry is known as a critical sector responsible for 38 % of total carbon dioxide emissions and 35 % of final energy consumption worldwide [3].

Although the statistics reveal that the European initiatives to reduce the buildings energy consumption already halved the consumption of new buildings compared to those constructed over two decades ago, around 85 % of the EU building stock was built over 20 years ago and 85 % to 95 % are expected to remain in operation until 2050 [4]. This, alongside the low recorded renovation rate in the EU building sector (currently estimated at around 1 % per year), highlight the importance of energy retrofitting of buildings as crucial initiative for enabling the EU member states to achieve their climate-neutral goals.

Accordingly, the EU has set the ambitious goal to reduce GHG emissions by 55 % by 2030 and up to 90 % reduction by 2040, both compared to the emission level in 1990, with the aim to become the first climate-neutral continent by 2050 [5]. Such targets require a paradigm shift in the economy of the EU member states including but not limited to the building sector. Here, in the field of construction, the European Commission provides key regulatory guidance to address the design of all new buildings in nearly zero energy since 2021 [6], and zero emission from 1 January 2027 [7]. Moreover, the Commission aims to at least double the building renovation rate over the next ten years [8].

Currently, the operational energy needed for heating, cooling, and domestic hot water production in the EU households is around 80 % of the total building energy demand [6]. Nevertheless, improving the operational energy efficiency of buildings rises concerns about the overall environmental performance of building, in the sense that it typically shift the environmental burden from the operational impacts to

* Corresponding author.
E-mail address: fabrizio.leonforte@polimi.it (F. Leonforte).

https://doi.org/10.1016/j.enbuild.2025.116357
Received 30 March 2025; Received in revised form 21 July 2025; Accepted 22 August 2025
Available online 24 August 2025

Nomenclature

ADP elem	Abiotic Depletion Potential for elements
ADP fossil	Abiotic Depletion Potential for fossil fuels
AP	Acidification Potential
BACS	Building Automation and Control System
BEMS	Building Energy Management System
BIPV	Building Integrated Photovoltaic
CAT	Calculation and Assessment Tool
DHW	Domestic Hot Water
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FU	Functional Unit
GBRSs	Green Building Rating Systems
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communication Technology
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MIMO	Multi Input Multi Output (converter)
ODP	Ozone Depletion Potential
PCM	Phase Change Materials
POCP	Photochemical Ozone Creation Potential
TES	Thermal Energy Storage

the embodied impacts associated with construction materials and systems [9]. Some estimates claim that in 2050 the share of embodied impacts of new constructions will be coming out ultimately like the operational impacts [10]. To go beyond the use phase, the need for whole life cycle approach becomes increasingly urgent, calling for Life Cycle Assessment (LCA) to scientifically measure the wide range of environmental impacts across all life cycle stages of buildings. Indeed, LCA method ensures that the impacts of the production (A1-A3), construction (A4-A5), use (B1-B7), and end-of-life phases (C1-C4), alongside the load and benefit beyond the system boundary (D), are comprehensively assessed in compliance with the well-recognized international standards. In such framework, ISO 14040 [11], ISO 14044 [12], EN 15978 [13], and EN 15804 [14] are commonly followed by LCA practitioners for the most various purpose and scope in the construction sector, pointing out the methodological assumptions and further technicalities of implementing LCA studies in building projects [42].

Another way to help stakeholders to improve building performance while reducing their environmental impact is the application of the so-called Green Building Rating Systems (GBRSs). They are known as holistic frameworks to evaluate and certify the sustainability performance of buildings, by determining the sustainability levels based on multiple criteria [15]. So far, numerous GBRSs have been developed globally and discussed and compared in the literature [1617]. The common feature is the criteria-based scoring systems that rely on a mixed qualitative and quantitative assessment approach making them an appealing tool for the building industry as can facilitate the overall sustainability rating of buildings [18], although in some instances criticized for neglecting local effects and priorities [19]. In comparison with LCA, GBRSs are designed to cover not only the environmental performance of the building but also economic and social issues, such occupant health and quality of life, while LCA deals uniquely with the quantitative assessment of environmental performance. GBRS and LCA frameworks serve thus different aims and follow diverse methods to measure the sustainability level of buildings [18], but the importance of integrating LCA into GBRSs is emphasized to enhance the quality and robustness of the environmental performance assessment [2021].

In this context, Level(s) – acronym of Life cycle, Environmental performance, Verification, Environmental impact, and Life cycle cost – is a recently developed framework at the EU level aiming at providing a common language to assess, report and improve the sustainability performance of building throughout the value chain. It introduces multiple macro-objectives, each of which with a set of indicators, focusing on three main thematic areas: a) resource use and environmental performance, b) health and comfort and c) costs, values, and risk [22]. Contrary to some GBRSs, which may include building-level LCA analysis as one of the evaluation criteria, Level(s) uses LCA as fundamental tool to measure environmental impacts across all building life cycle stages, providing a standardized, science-based methodology that aligns with European sustainability objectives. As a result, Level(s) is now at the core of the policy framework, playing an important role for the sustainable building projects across Europe and increasingly steering certification schemes and public procurement criteria of EU member states.

Given the utmost importance of the aforementioned sustainability assessment methods and tools and the highest priority of building energy retrofitting in achieving the climate-neutral targets of the building sector, the paper discloses the environmental performance of a smart energy retrofit project within the EU context, performing building-level LCA aligned with Level(s) framework. Indeed, despite the growing emphasis on sustainability in the built environment, the application of Level(s) framework remains relatively unexplored in the scientific literature, with a notable absence of benchmarks assessing its implementation in deep energy retrofit projects. To fill this gap, the present study systematically applies Level(s) to assess the GWP of a deep energy retrofit case, aiming to establish reference values for the creation of benchmarks intended to facilitate future comparative analyses and fosters the wider adoption of the framework in the field of sustainable building practices.

For offering a more comprehensive overview, Level(s) framework is primarily introduced and discussed in terms of compatibility with the GBRSs currently available and the standardized LCA methods, by reviewing existing studies. Afterwards, a representative residential building retrofitted in Italy has been selected as a case study from HEART H2020 project [23]. Funded by EU Horizon program, HEART is a multifunctional retrofit toolkit within which different technologies cooperate synergistically to transform an existing building into a smart building. Based on a whole-building performance approach, the toolkit is conceived to achieve extremely high levels of energy efficiency in the existing building stock and to undergo an LCA analysis, addressing both embodied and operational impacts. The key environmental indicator for Level(s) framework (but also most GBRSs and building policies), namely Global Warming Potential (GWP), and further LCA indicators have been used to demonstrate the effectiveness of energy retrofit scenarios designed and implemented in the buildings. The aim is to assess a real building project subject to smart energy retrofit using LCA method in compliance with Level(s) framework, as well as ISO/EN standards. Due to the adherence to standardized methods, practical focus on real-world applications and alignment with global sustainability metrics, the presented LCA results are expected to become reference values for benchmarking and for advancing the sustainability of the built environment retrofitting by the use of innovative technological solutions.

In such a context, the goal for the specific building project is twofold. Firstly, to provide a holistic assessment, by ensuring that the reduction in operational impacts throughout the building life cycle outweighs the increase in embodied impacts, and thus an informed decision-making with optimized retrofit solutions for minimal environmental footprint. Secondly, to improve the environmental credentials of the project but also enhance its market value and stakeholder acceptability, particularly in a background where financing is increasingly linked to demonstrable sustainability outcomes.

2. Literature review — Level(s) framework in practice

As briefly anticipated, Level(s) aims to provide a common and unified assessment and reporting framework for the sustainability performance of buildings aligned with European standards and climate targets. It is organized into three levels, namely Level 1 (L1) Conceptual design, Level 2 (L2) Detailed design and construction, and Level 3 (L3) As-built and in-use. Since designed in line with the building process, the progression up the levels represents an increase in data accuracy and reliability: the higher the level, the closer the reported results will provide data that reflects the real performance of building. Starting from the thematic areas, the framework is closely aligned with the three sustainability pillars – known as environmental, social and economic – further breakdown into 6 macro-objectives and 16 indicators to measure buildings sustainability [22], as displayed in Table 1.

To fully support the whole life cycle approach, the core indicators of macro-objectives 1, 2 and 3 are complemented by a holistic assessment of building environmental impact: a full LCA of a building, focused on Global Warming Potential as key environmental impact categories and compliant with EN standards. In addition, to push its practical application, alongside several user manuals already published to guide built-environment stakeholders on how to measure each Level(s) indicator, the European Commission has introduced a free access tool known as Level(s) Calculation and Assessment Tool (CAT) to facilitate the implementation of Level(s) framework and compare design alternatives at each of the three levels and according to each macro-objective and indicator [24].

Despite that, so far only few studies have evaluated the applicability of Level(s) as new framework for sustainability assessment of buildings, highlighting from different perspectives the existing challenges of its application. For instance, Diaz-Lopez et al [25] evaluated the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of Level(s), drawing attention to several issues. The main top-rated strength factors of Level(s) framework are its position as the common language for comparing the sustainability of buildings in the whole of Europe and the support provided by the European Commission. On the other hand, the main weakness is found in the complexity of the user guide in its current versions. The Level(s) capability to address the need for climate change adaptation of the building sector and its alignment with sustainable and circular economy policies are stated as the top two opportunities. Finally, the fact that there is not yet a European directive to ensure its full implementation and the high level of uncertainty of required data for the assessment are reported as the top two threats of Level(s) in its current stage.

Birgisdottir & Haugbølle [26] explains the main challenges of implementing the Level(s) framework according to the lessons learned from 18 case studies in Denmark. In particular, the difficulty and complexity of the framework manuals are emphasized as first challenges realized in applying Level(s). Furthermore, they experienced that implementing Level(s) at Levels 2 and 3 is highly resource-demanding requiring numerous data that might be challenging to collect. Another challenge is the lack of benchmarks which makes the results difficult for the sake of comparison among different projects. Thus, several recommendations to improve Level(s) are suggested such as simplifying the user guides, creating more user-friendly tools aligned with manuals, and providing baseline to compare and interpret the results obtained for projects. The need for providing national and contextual-based benchmarks is particularly emphasized as a requirement to effectively implement the Level(s) framework for renovation projects.

Likewise, a study to test the framework in Finland has been carried out on more than 20 construction projects, confirming several challenges including the complexity of the user manuals, the time-consuming process of data collection and the lack of clear added value offered by the EU framework compared to existing Green Building Rating Systems such as DGNB [27].

With a focus on circularity, Honic and De Wolf [28] have applied Level(s) on a building case study according to indicators 2.1 (Bill of quantities, materials, and lifespans) and 2.2 (Construction and demolition waste and materials), to provide a better understanding of how it can be used in practice. As weakness of the framework, they noted that some parameters, such as the type of connections between layers that may have significant impact on the reusability/recyclability potential of materials, are not considered in the selected indicators. In addition, the complexity of the Level(s) documents in explaining the framework is recalled, as well as the expertise required by users as barriers for the

Table 1
Overview of Level(s) thematic areas, macro-objectives and corresponding indicators [22].

Thematic areas	Macro-objective	Indicator	Unit of measurement
Resource use and environmental performance	1: Greenhouse gas and air pollutant emissions along a building's life cycle	1.1 Use stage energy performance	kilowatt hours per square metre per year (kWh/m^{2}y)
		1.2 Life cycle Global Warming Potential	kg CO_2 equivalents per square metre per year (kg CO_2 eq./m^{2}y)
	2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials and lifespans	Unit quantities, mass and years
		2.2 Construction & demolition waste and materials	kg of waste and materials per m^2 total useful floor area
		2.3 Design for adaptability and renovation	Adaptability score
		2.4 Design for deconstruction, reuse and recycling	Deconstruction score
	3. Efficient use of water resources	3.1 Use stage water consumption	m^3/yr of water per occupant
	1–3. Full LCA	n/a	10 impact categories
Health and comfort	4. Healthy and comfortable spaces	4.1 Indoor air quality	Parameters for ventilation, CO_2 and humidity, Target list of pollutants: TVOC, formaldehyde, CMR VOC, LCI ratio, mould, benzene, particulates, radon
		4.2 Time outside of thermal comfort range	% of the time out of range during the heating and cooling seasons
		4.3 Lighting and visual comfort	Level 1 checklist
		4.4 Acoustics and protection against noise	Level 1 checklist
Cost, value and risk	5. Adaptation and resilience to climate change	5.1 Protection of occupier health and thermal comfort	Projected % time out of range in the years 2030 and 2050 (see also indicator 4.2)
		5.2 Increased risk of extreme weather events	Level 1 checklist (under development)
		5.3 Increased risk of flood events	Level 1 checklist (under development)
	6. Optimised life cycle cost and value	6.1 Life cycle costs	Euros per square metre per year (€/m^{2}y)
		6.2 Value creation and risk exposure	Level 1 checklist

implementation of indicators.

Ramon et al [29] concentrated around the Level 1 of Level(s) on an office building in Belgium, pointing out that although L1 assessment provides insight into various aspects of building performance, it does not make a clear evaluation of the sustainability level. The application of Level(s) framework on higher levels (L2 and L3) is considered more useful to assess the sustainability of buildings, even the lack of reference values (benchmarks) to compare the obtained results.

A study by Miguel and Silva [30] has explored Level(s) framework in action, arguing each indicator separately. Several critical areas of Level (s) implementation are identified, to name a few: the technical complexity of user manuals, the framework reliance on multiple EN standards not freely accessible by practitioners, the dependency on third-party assessment tools and resources, and the absence of reference values and benchmarks for interpretation of the results. Concerning more specifically the full-LCA promoted by Level(s), another barrier refers to the lack in some geographic contexts of sufficient environmental data implying the use of less-accurate international data to assess life cycle impacts [31]. For instance, due to missing life cycle inventory within a specific region or country, it might be inevitable to adopt data from another region. However, it is worth mentioning that it is a general barrier for LCA in the environmental assessment of buildings, not only attributed to Level(s) [32].

Benefits and drawbacks of Level(s) are lastly considered by Elias [33], reiterating valuable areas of improvement such as the simplification of the user manuals to reduce the complexity of the application, and revealing the need of integration with other well-established tools such as Building Information Modeling (BIM) and LCA software. In this respect, the fact that Level(s) reporting is not digitalized is an obstacle to its integration into BIM/LCA tools, posing an issue that have to be further addressed in the future, just as the common rating of building environmental performance based on reference values.

In summary, the application of the Level(s) framework for sustainability assessment of buildings faces the following challenges listed in Table 2.

To address these limitations, a joint effort is required to spread in Europe the sample of building case studies assessed trough Level(s) framework, for providing practical evidence-based insights that help bridge the gap between theoretical frameworks and real-world application, especially in relation to the need for reference values for the creation of benchmarks for sustainable practices.

2.1. *Green building Rating systems and Level(s) – the synergy among the frameworks*

In literature, till now there are few studies that investigate the degree of synergy and affinity between the Level(s) framework and the Green Building Rating Systems (GBRSs), for measuring the proximity of the building to the sustainability targets.

Table 2
The summary of the challenges of the application of the Level(s) framework.

N.	Challenge	Description
1	Complexity	User manuals are often complicated and tricky to understand, making the framework hard to implement in practice.
2	Extensive data requirement	Applying Level(s), especially at higher levels, requires extensive and often difficult-to-obtain data.
3	Lack of benchmark	The absence of benchmarks makes difficult to compare results across different projects and assess sustainability levels effectively.
4	Lack of interoperability	The framework current format hinders its integration with other tools like BIM and LCA.
5	Lack of performance scale	The framework does not provide a direct rating for buildings, making it difficult to interpret results in a straightforward manner.

Among them, Cordero et al [34] explored the most widespread sustainability certification within Europe, including BREEAM, LEED, HQE, and DGNB, electing the latter as the most aligned rating systems with Level(s), the current official EU framework. They have also advised that the future version of LEED, BREEAM, and HQE will have a crucial role in aligning and harmonizing these frameworks.

By contrast, the study of Santos et al [35] comes up with different results, comparing nine GBRSs applied globally and concluding that BREEAM, LEED, and DGNB are most consistent with Level(s), covering 14, 13, and 11 out of the 16 indicators, respectively. Going into detail, they have stated that BREEAM fails to address the indicators 2.4 (Design for deconstruction, reuse, and recycling) and 6.2 (Value creation and risk factors). The indicators 5.1 (Protection of occupier health and thermal comfort), 6.1 (Life cycle costs) and 6.2 (Value creation and risk exposures) are missing in LEED. However, to be keep in mind that some indicators might be implicitly targeted in other criteria within GBRSs. They also highlighted that if BREEAM turns out to be the most aligned GBRS to Level(s), LEED and DGNB due to their higher level of quantitative nature are closer and represent higher levels of commitment to the EU carbon neutral goals [35].

Ferrari et al [36] have defined the affinity levels between Level(s) and five well-known GBRSs according to three viewpoints, including the correlation degree between the criteria addressed in each GBRS and the macro-objective in Level(s), the standards recommended for the calculation method and the coverage of building life cycle stages. They showed that LEED has the highest level of affinity with Level(s) macro-objectives, reaching 81 % while BREEAM and DGNB 73 % and 68 % of the macro-objectives respectively. Nevertheless, they realized that DGNB followed by BREEAM has better alignment with Level(s) framework in terms of similarity of the standards adopted for calculation methods and higher affinity levels with Level(s) regarding the life cycle stage coverage.

As shown in this section, different studies on the alignment of GBRSs and Level(s) framework have reported diverse results and conclusions, depending on the topics at issue. Although most agree that the main three GBRSs – namely LEED, BREEAM and DGNB – have an acceptable degree of affinities with the Level(s) framework, they have concluded different statements on their correlation degree with Level(s) framework. The variety of comments and conclusions in this regard might have originated from the complexity of Level(s) guidelines that make the comparison more difficult to obtain a holistic understanding. Nonetheless, almost all studies on the matter reaffirm the need for clarifying the relationship between GBRSs and Level(s) to better orient stakeholders in the choice and adoption of sustainability assessment framework.

2.2. *Life cycle assessment and Level(s) – the methodological affinity*

Level(s) framework aims to promote life cycle thinking, guiding users from an initial focus on individual aspects of building performance, via the indicators, towards a more holistic perspective, meant to expand European use of Life Cycle Assessment (LCA) but also Life Cycle Costing (LCC) methods. In particular, by making a LCA, the environmental impacts associated with buildings are quantified and the most significant areas – commonly referred to as “hotspots” – can be identified and used as the starting point for improving performance. Following LCA EN standards, the final goal is to measure the performance of buildings and their contribution to the core indicators of macro-objectives 1, 2 and 3. In Level(s), LCA results are reported in detail into indicator 1.2 (Life cycle Global Warming Potential) for each life cycle stage and involving potentially other impact categories than GWP [22]. Nevertheless, despite the strategic role, the integration of LCA methods into the Level(s) framework has been discussed in limited studies from diverse viewpoints.

De Wolf et al. [37] outlined the need for classifying tools and databases according to a list of parameters and criteria addressing three key aspects that they offer in varying degrees: comprehensiveness, robustness, and operability. Here, comprehensiveness refers to several aspects such as the coverage of life cycle stages, accounted environmental indicators and modelling granularity. Robustness concerns the methodological alignment of LCA tools with EN 15978/15804 standards, the check on data quality in terms of geographical, temporal, and technological representativeness, as well as software transparency and verification. Operability addresses practical aspects such as the accessibility of tools/databases, the cost and training levels necessary to use the tools, and their interoperability with other design software. These criteria have been discussed in relation to the adaptation of LCA tools and databases, including OpenLCA, One Click LCA, GaBi, and SimaPro, stressing the need to develop more accessible tools for facilitating the assessment process.

Regarding data source required for implementing LCA within the Level(s), but even DGNB certification, Del Rosario et al [38] assessed a case study and affirm that adopting the Environmental Product Declaration (EPD) does not align with the mandatory scope of both frameworks, with the risk of inadequate assessment when EPD is used as the single reference source. Another constraint of using EPDs pertains the disaggregated reporting requirements of Global Warming Potential (GWP) in the Level(s) framework, demanding GWP impacts separately for fossil, biogenic, and land use following EN 15804:2012 + A2:2019, while most of available EPDs are created using the older version of EN standard. In this way, they turn out mostly not qualified for the reporting format according to the Level(s) requirements.

In another study, Palumbo et al [39] examined the influence of different system boundary definitions to conduct LCA according to Level (s) framework. For this purpose, they defined two simplified methods based on the covered life cycle stages, where the first includes A1-A3 and B4-B6 and the second includes A1-A3, B6, C3, C4 and D. The case studies analysis proved that results are mainly determined by the operation phase (B6), finding a difference of less than 1 % of the total GWP between the two modelling. Besides, they advised harmonizing the LCA application among GBRSs, especially regarding the data availability according to the design process and mandatory stages of the LCA application.

Finally, Erlandsson et al [40] evaluated the setting and applicability of LCA in Level(s), highlighting its potential to enhance environmental performance assessment in the construction sector. Integrating digitalization approaches, like BIM, is strongly recommended to streamline the LCA process. The adoption of BIM not only facilitates data collection and management but also improves the accuracy and reliability of results. Furthermore, this integration supports better decision-making by enabling real-time environmental performance analyses throughout the project lifecycle. By leveraging digital tools like BIM, the effectiveness and user-friendliness of LCA within the Level(s) framework can be significantly enhanced.

3. Materials and methods

This study is developed with the primary goal of quantifying the environmental impacts of deep energy retrofit interventions on a representative residential building, performing LCA following ISO 14040/44 and EN 15978 standard consistently with Level(s) framework. Notably, since the main goal at EU level is to achieve decarbonization, and thus reduce GWP, the macro-objectives 1 and 2 of Level(s) are considered, including the use stage energy performance as operational impacts and the implementation of building technologies as embodied impacts. Through the LCA analysis, the potential environmental impacts associated with the pre-retrofit and post-retrofit scenarios are compared and the environmental payback period is calculated and presented.

3.1. Methodology

The system boundary of the study is defined to cover the main and most impactful life cycle modules during retrofit project, consisting of refurbishment (B5) and operational energy (B6) in the use stage. Indeed, in compliance with Level(s) calculation rules for LCA, in major renovations of existing buildings – like in the context of HEART project – the system boundary encompasses all life cycle stages that relate to the extension of the building service life. In practice, this means B1 onwards as the stages relating to the original production (A1-A3) and construction (A4-A5) have already taken place. Accordingly, the *cradle-to-gate* LCA analysis of HEART technologies refers to B5 refurbishment, intending the modification and improvements to the existing building to bring it up to an acceptable condition, whilst disregarding the installation process since considered negligible. Out of the scope are the life cycle modules related to maintenance (B2), replacement (B4), end-of-life (C1-C4) and benefits and loads beyond the system boundary (D).

The choice to focus only on the upstream stages is aimed at improving the know-how on building technologies relating to innovative system not yet established in terms of environmental profile. In fact, if until recently LCA studies for the building sector occurred on a voluntary basis, by measuring the environmental impacts allocated to the construction flows in the whole life cycle, it is only with the recast EPBD [6] that life-cycle GWP is becoming mandatory (from 2028 onwards), progressively according to building size and extending LCA scope. Accordingly, building elements are in the spotlight as well as the technical equipment, in line with what defined in the Level(s) common EU framework for indicator 1.2. This implies the need to assess the environmental impact of plant systems, requiring manufacturers to equip themselves, for instance, with Environmental Product Declaration (EPD), today still underdeveloped for this product category, to not relying on database to avoid being disadvantaged. The effort of the present work is therefore to initiate the assessment process, starting to bridge this gap for HEART technologies, by raising awareness of how they impact the environment and the importance of affecting the entire supply chain towards sustainability, given the complexity of systems and the intricate procurement of related components and sub-components. In addition, downstream stages are not considered due to too high levels of uncertainty both in terms of replacement cycles and systems efficiency over time (operational use) and in terms of impact assessment of decommissioning operations (end-of-life). From this point of view, the presented building case study intends to serve as experimentation ground in monitoring everything concerning maintenance during the operating life and the way in which components will be managed at the end of their useful life, even accounting the technological evolution in action especially with regard to the recycling/reuse industrial practices. Therefore, the assessment is narrowed down to what precisely calculable with reliable data now at our disposal.

Within the paper, the life cycle inventory relies on different sources of data, constrained by the specificity of the case study, prioritizing whenever applicable primary data and for background data using Ecoinvent v3.7.1 [41], as the most completed, reliable and transparent database. Primary data are used for the retrofit technologies (B5), collecting them by the HEART project industrial partners through dedicated spreadsheet and additional information exchanges to ensure high-quality data for building retrofitting. In this way, they are specific to the actual processes, materials, and activities associated with the peculiar design solution, providing high accuracy of the inventory with good temporal, geographical and technological representativeness. The energy consumption of pre-retrofit scenario (B6) depends as well as on primary data, retrieved by collecting natural gas and electricity bills. Instead, the energy consumption related to heating, cooling and domestic hot water of post-retrofit scenario is modelled by using EnergyPlus software.

The life cycle impact assessment follows the CML LCIA method V3.05 [41], evaluating in total seven different environmental indicators: Global Warming Potential (GWP) – as key indicator – and Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Abiotic

Depletion Potential for elements (ADP elem.), Abiotic Depletion Potential for fossil fuels (ADP fossil), as further LCA indicators. The aim is to provide a comprehensive and holistic evaluation of the GWP along with other environmental impacts derived from building retrofitting.

In accordance with Level(s), the Functional Unit of the building-level LCA study is a square meter of useful internal floor area, here reported per service year (FU = 1 m^2y). Concerning the normalization, the environmental impacts per year of use are calculated based on the actual lifespan of the individual technologies, rather than relying on a fixed reference study period of 50 years. Specifically, the production-related impacts of each technology are scaled to a single year of service, by their proportional distribution over the expected service life. It means that if the component lifespan is 10 years, as for smart fan coil, only one-tenth of its production impacts is considered and attributed to a single year of use. This methodological approach greatly enhances the generalizability of the results, allowing their flexible use in measuring environmental performance. Indeed, by expressing impacts on a properly per-year basis, the environmental profile of different technologies can be evaluated independently of the total study period. Although with appropriate simplifications, findings remain applicable and transferable across different building projects and scenarios, even when the pre-determined study period does not match up, supporting stakeholders to make informed decisions-making over time. In addition, in the normalization process, the useful internal floor area refers to the real-case residential building, subject to the energy retrofitting project, described below.

3.2. Building case study

The building serving as the object of analysis is the first case study of HEART project: a multifamily house located in Bagnolo del Piano, Reggio Emilia (Italy), with a total living space of around 740 m^2, distributed in 12 apartments and four floors above ground (the typical one is shown in Fig. 1), built in 1985. It is characterized by concrete load-bearing structure, masonry brick walls, poor performances envelope (e.g. wood frame single-glazing windows, uninsulated roof, low-insulated façade) and equipped with low-efficiency natural gas boiler and traditional hydronic radiators for heating and electric domestic hot water heaters. The building, has been subject to renovation in 2020 with HEART "Holistic Energy and Architectural Retrofit Toolkit". It is a multifunctional toolkit dedicated to buildings energy retrofit within which tools and components – ICT, BACS, HVAC, BIPV and Envelope Technologies – cooperate organically to achieve high levels of energy efficiency (Fig. 2).

By the application of the HEART retrofit toolkit (Fig. 3), the building envelope has been insulated using pre-shaped modular insulation panels, namely lightweight sandwich panels composed of low-conductivity insulation core and two thin steel layers, mounted on the existing façades, existing windows have been maintained and retrofitted installing new high-performance double-glazing. The new heating system is based on a centralized configuration that includes two direct-current air-to-water heat pumps (DC-HPs) to pre-heat/pre-cool the building water loop. Connected to the latter there are DC smart fan coils installed in each room, which acts as water-to-air decentralized heat pumps, heating up/cooling down ambient air by means of a vapor-compression circuit. A Thermal Energy Storage (TES) is also connected to the water loop, to store sensible/latent heat by means of water added with Phase Change Materials (PCM) spheres. These are inserted in 3 water tanks with a total capacity around 120 kWh. The PCM has phase change at 25 °C with melting/solidification area from 24 to 32/27–23 °C. Temperatures in TES unit are approximately 32–34 °C during winter and 16–18 °C during summer to achieve inlet temperature in the heating system around 25 °C. The TES unit satisfies the boundary conditions of the considered heating system, where the optimal water supply temperature to the fan coils is 25 °C and the return temperature to the centralized heat pump is 15–20 °C. The DC-HPs supply heat both to the heating system and/or to the TES for load-shifting, to ensure the operation of DC-HP at the most favorable conditions (e.g., higher ambient air temperature, availability of solar energy, etc.). Moreover, a photovoltaic system consisting of innovative PV tiles on a recycled plastic support base has been integrated with roofing, providing a total power of 8.7 kW_p. The logic of the control system allows the TES to properly shift load there is PV overproduction not consumed onsite. The DHW is produced by water-to-water decentralized heat pumps boilers connected to the same water loop mentioned before. An overview on the energy supply system is shown in Fig. 4.

The thickness of thermal insulation and the size of different components (e.g., PV system and TES) have been determined using a decision-support process to identify the cost-optimal option. Furthermore, a battery with a capacity of 14 kWh has been installed into the

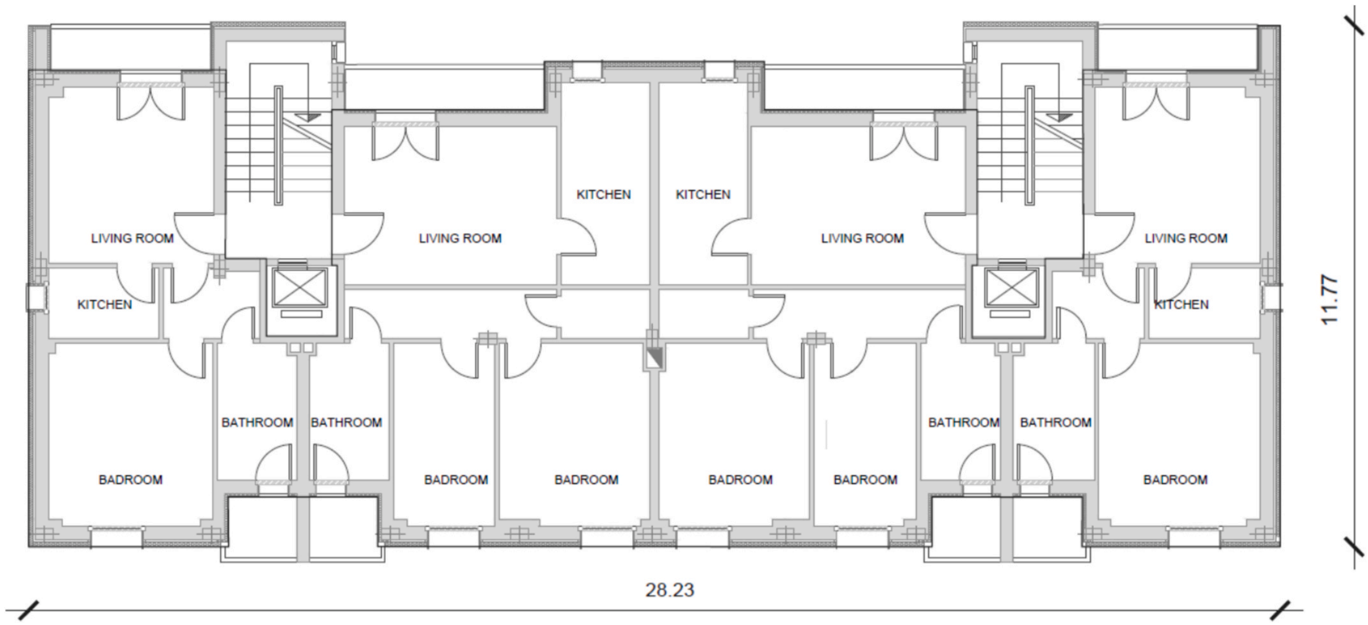

Fig. 1. Typical floor of the building.

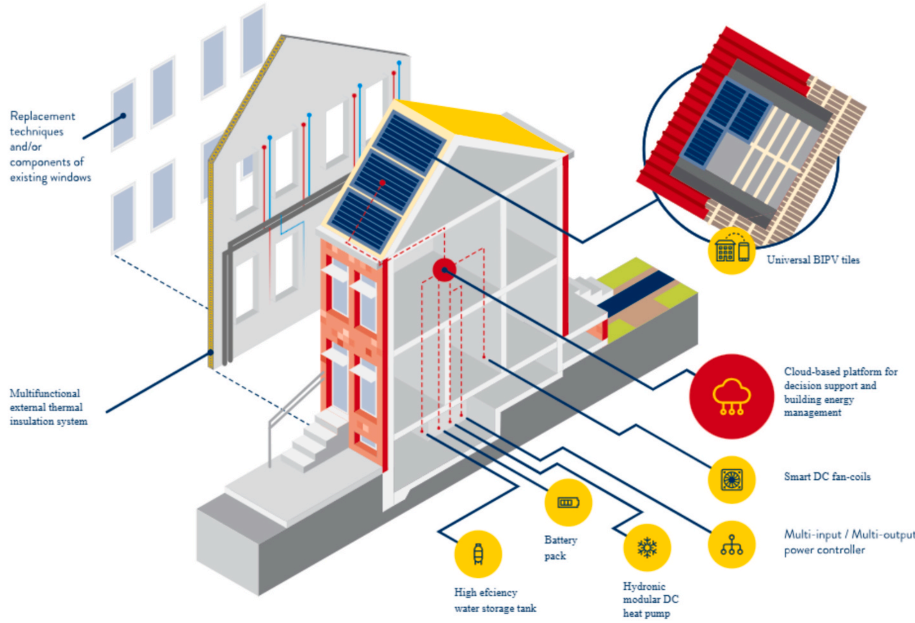

Fig. 2. Scheme of the HEART toolkit.

Fig. 3. View of the building after the retrofit process.

building, with the aim to store electricity when the TES is full or the thermal energy is not needed in the building (e.g., mid seasons). The Building Energy Management System (BEMS) controls electricity/thermal energy fluxes, as well as coordinates the main devices (e.g., heat pumps, fan coils, etc.) on the basis of different variables (e.g., PV energy production, building load, etc.).

Table 3 displays the retrofit solutions according to the reporting format for building-level LCA required by Level(s) framework, focusing on envelope and plant services, excluding external works since out of the system boundaries. For each new technology, it provides details on the dimensions, quantity and lifespan considered in the LCA modelling.

4. LCA analysis

This section presents the LCA results in two parts: the first one shows

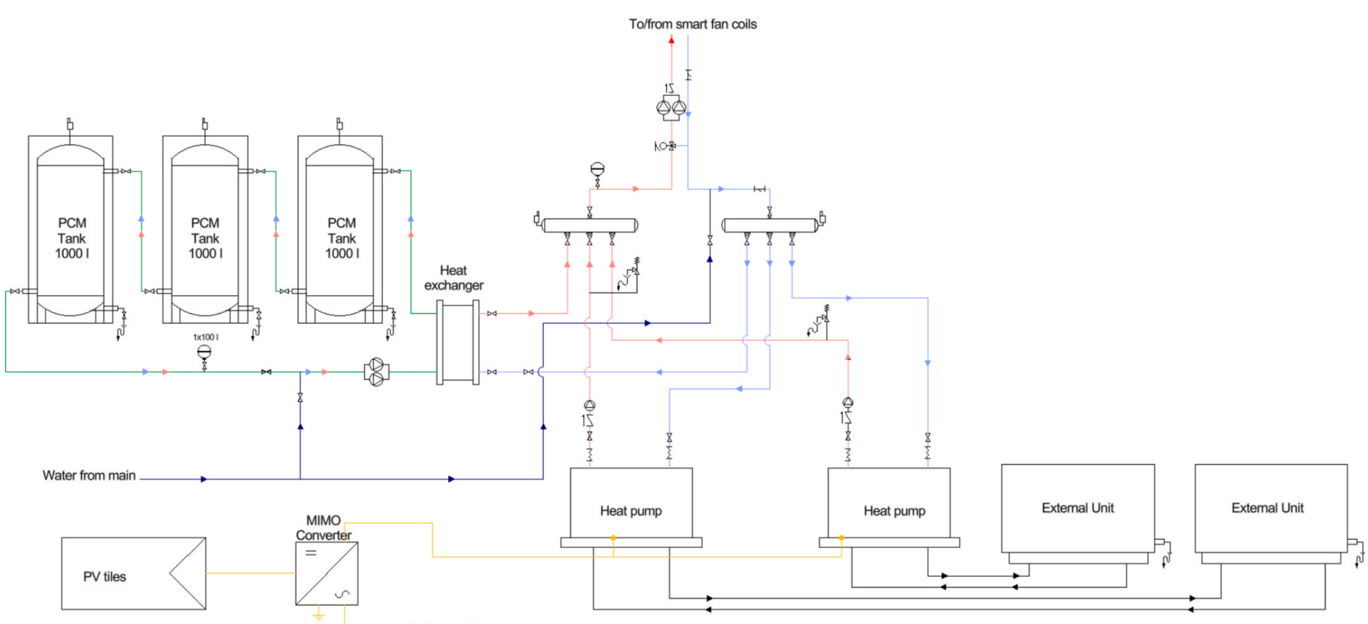

Fig. 4. General scheme of the energy supply system.

Table 3
Technological solutions of post-retrofit building, in compliance with Level(s) reporting.

Building parts	Building elements	Post-retrofit
> Shell (substructure and superstructure)		
Facades	External wall systems, cladding and shading devices	– Modular façade thermal insulation panels, 10 cm thick, 702 m^2, 40 years lifespan (solution for building envelope) – Modular façade thermal insulation panels, 5 cm thick, 380 m^2 surface, 40 years lifespan (solution for window intradoses and loggias)
	Façade openings	– New double-glazing, 107 m^2, 20 years lifespan
Roof	Weatherproofing	– Roof insulation in EPS, 226 m^2, 40 years lifespan
> Core (fittings, furnishings and services)		
Energy system	Heating and cooling plant and distribution	– DC heat pump (with r410a, refrigerant, 199x150x144cm external unit, 160x59x55cm internal unit), 2 pieces, 15 years lifespan – Smart DHW boiler (80 L each), 12 pieces, 10 years lifespan – Thermal Energy Storage (TES), 3 pieces (1000 Liters each), 30 years lifespan (the LCA modelling includes the set of nodules with Phase Change Materials (PCM) with 21 years lifespan)
	Radiators	– Smart fan coils, 30 pieces, 10 years lifespan
	Electricity generation	– PV tiles, 88 m^2, 20 years lifespan (the LCA modelling includes the single-Si laminate, the plastic support base and related transports)
	Electricity distribution	– Multi-input/multi-output (MIMO) converter, 1 piece, 30 years lifespan – Battery pack, 4 pieces, 10 years lifespan

the impacts obtained for Global Warming Potential (GWP), established as key indicator in Level(s), by covering the macro-objective 1 "Greenhouse gas emissions along a building's life cycle" and including both embodied and operational emissions. The second part presents further LCA environmental indicators, to go a step forward as required by Level (s), in order to avoid an over-reliance on GWP which risks neglecting critical areas of sustainable development. Indeed, while GWP is undeniably essential for measuring progress toward climate neutrality, in line with LCA method it must be viewed within a broader context and balanced with other sustainability metrics, to ensure a truly holistic approach to building performance. For this reason, beyond GWP, six additional environmental indicators are reported. The discussion is taken at the different scales: from building-level, comparing pre-retrofit and post-retrofit scenarios, to product-level, providing LCA insights for each technology implemented during the energy retrofit. Finally, the net GWP reduction over the building life span and environmental payback period is provided and elaborated.

Specifically, the LCA environmental impacts of the Italian case study are accounted as follows:

1 – New technologies – namely the set of installed HEART technologies required for building retrofitting, falling under the module B5 refurbishment, in accordance with Level(s), incorporating their *cradle-to-gate* LCA analysis. Note that the impacts per year of use are calculated based exclusively on the actual lifespan of the technologies. In this way, the production impacts of each technology are scaled to one year of use, offering the chance to multiplying the annual impacts by a reference study period, such as the 50 years suggested in the Level(s) framework. However, it is worth mentioning that this practice presents both significant advantages and certain limitations. Among the main advantages is the opportunity to evaluate the environmental profile regardless of the reference study period, enabling the generalization of results across different buildings and retrofit scenarios. In this respect, emblematic is the case of modular façade panel with a lifespan of 40 years, which in a conventional 50-year assessment require one full replacement, with the second cycle covering only 10 years of use. This result in disproportionately high impacts allocated to the second cycle, since the residual performance of the component beyond the 50-year timeframe is not considered. By normalizing impacts on a technology-specific yearly basis, such distortions are avoided, thereby enabling a more balanced and flexible evaluation. On the other hand, a key limitation of this approach is that it neglects to fully account the impacts associated to the downstream phases with maintenance and replacement operations over time. In the event that the normalized annual production impacts are multiplied by the reference study period to estimate total impacts, it is like considering in the replacement only the production of the new component. Transport to and from the construction site and the disposal of the replaced component would be excluded. Nevertheless, given the presence of well-established recovery and recycling practices – especially for metals and electronic parts, which represent major constituents of the technologies under study – these aspects can be considered negligible (cut-off). As evidenced in Table 3, the new building-integrated technical solutions are distinguished by different lifespan, calling for dissimilar replacement cycles over the reference timeframe.

2 – Energy consumption – namely the operational energy impacts, determined by energy measurements of heating, and domestic hot water, not counting the personal appliances of inhabitants. The amount of energy used by building-integrated technical systems during the operation of the building refers to B6 operational energy use. It should be noted that the analysis does not include space cooling, as the pre-retrofit building was not equipped with such systems. Thus, in order to ensure comparability of results across the pre-retrofit and post-restrofit scenarios, cooling demand was excluded from the evaluation, despite the fact that the HEART toolkit is fully capable to provide it.

Moreover, the existing building, namely the stock of construction materials and plant services already in place before building renovation, covered in the A1-A3 life cycle stages, is not considered, since it is common to the post-retrofit interventions.

4.1. GWP as key indicator

As well-recognized, Global Warming Potential (GWP) is at the core of the scientific and public interest to quantify the environmental impacts of a building along its life cycle. This indicator encompasses both the greenhouse gas emissions embodied in building materials and the direct and indirect emissions from use-stage performance, such as energy consumption. The assessment boundary includes thus the "operational" emissions, those directly associated with the energy used for heating, cooling and supplying electricity to the building (B6), and the "embodied" emissions, here limited to renovation technologies and components (B5) as scope of work. In line with Level(s) requirement for LCA, carbon emissions are allocated to the life cycle stage where they occur, therefore attributing the emissions from new building materials used during renovation to the use stage. By comparing pre-retrofit and post-retrofit LCA results, this indicator reveals the effectiveness of retrofitting strategies in reducing GWP contributions over time, by measuring the performance enhancement from an environmental point of view but also with economic effects.

The embodied emissions for the post-retrofit scenarios were calculated according to Table 3, while the operational emissions were derived, in the case of the existing building, from electricity consumption data monitored over three years. In the case of the HEART, a mixed method based on both real data and simulations was used. More in detail, as the monitoring data relating to the operation of the system are only available for a limited period of time, due to the fine-tuning process of the components and the monitoring system itself, these data were used to calibrate a detailed simulation model, with which the post-retrofit consumption was then estimated on the basis of the actual climate data measured at the building. This made it possible to obtain consumption data from the post-retrofit phase over a period of time that was sufficiently representative of the purpose of the research.

The LCA results in Fig. 5, expressed in $kgCO_2eq$ per m^2 per year, successfully demonstrate the substantial GWP reductions through building retrofitting by HEART technologies, comparing pre-retrofit and post-retrofit scenarios of the building. Indeed, the total emissions turn out to drop from 39.71 $kgCO_2eq/m^2y$ pre-retrofit to 10.91 $kgCO_2eq/m^2y$ post-retrofit, making an overall decrease of 73 %. The clear breakdown of GWP by life cycle stages and, with regard to B5, per HEART technologies helps isolate the different contributions, aiding in targeted decision-making for retrofits.

In particular, by looking into data granularity, it is possible to detail contributions from new technologies (B5) and energy consumption (B6). As expected, the retrofit introduces an increase in GWP of 7.11 $kgCO_2eq/m^2y$, by accounting all the upstream emissions attributed to new construction technologies and advanced building plant systems. By contrast, energy consumption sees the most significant improvement, with a drastic reduction of 90 %, from 39.71 $kgCO_2eq/m^2y$ pre-retrofit to 3.79 $kgCO_2eq/m^2y$ post-retrofit. In fact, prior to retrofitting, the monitored amount of non-renewable primary energy was 154.70 kWh/m^2y, mostly gas powered from the existing boiler and only for a minor share sourced for grid electricity. As background system in the modelling, energy is calculated by considering electricity at 0.35 $kgCO_2eq/kWh$ for both direct and indirect emissions along the whole supply chain, on the basis of statistics of the year 2020 from IEA World Energy Statistics and Balances [41]. Instead, natural gas is accounted at 0.077 $kgCO_2eq/MJ$, targeted for central or small-scale heating [41]. On that ground, if the existing building shows overall inefficiencies in energy utilization due to the energy carrier and the technological obsolescence of building systems, the implementation of new retrofitting measures allows to substantially reduce the energy consumption. In fact, the electricity demand decreases to 10.77 kWh/m^2y, equal to 21 kWh/m^2y of non-renewable primary energy, resulting in lower environmental burdens and potentially cut operational costs associated with energy consumption (Fig. 6). This demonstrates the effectiveness of HEART retrofit, balancing operational and embodied emissions to achieve significant GWP impact reductions.

To provide embodied emissions estimation, the study presents in Fig. 7 the specific impacts associated to HEART technologies installed in

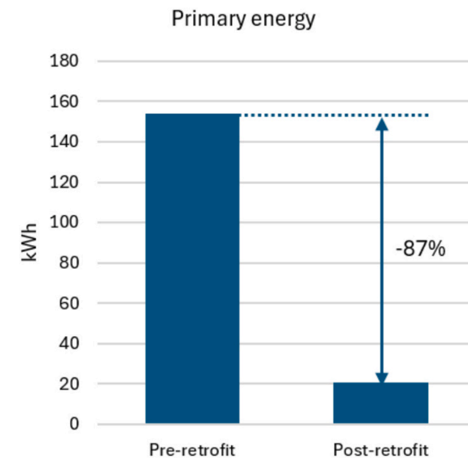

Fig. 6. Primary energy consumption before and after retrofit.

post-retrofit scenario, thus deepening B5 impacts at building-level in $kgCO_2eq$ per m^2 per year. The façade panels 10 cm thick shows the highest GWP contribution, reaching over 1.6 $kgCO_2eq/m^2y$, far exceeding all other measures and representing the 24 % of total GWP. This is mainly due by the extensive envelope surface to be insulated for energy-efficient building. Increasing façade insulation thickness implies an increased amount of material resources but significantly reduces heat loss and improve energy performance, in conjunction with the other plant systems. DC heat pump and smart fan coil follow, ranging from 1 to 1.2 $kgCO_2eq/m^2y$, contributing around 17 % and 14 % to the GWP, respectively. They both exhibit relatively high GWP impacts compared to other technologies, although they have high potential to decrease operational emission due to their potential to minimize the energy consumption during the use phase of the building. As medium-impacts technologies, façade retrofit 5 cm thick, placed in window intradoses and loggias, and PV tiles over roofing are evidenced, with average impact at 0.8 $kgCO_2eq/m^2y$, ranging from 10 % to 12 % of the total GWP. Smaller contributions are observed for solutions such as smart DHW boilers, roof insulation, TES with PCM spheres and window retrofit components, all falling below 0.4 $kgCO_2eq/m^2y$. MIMO converter and battery pack exhibit minimal GWP contributions, staying under 0.2 $kgCO_2eq/m^2y$.

In the light of this, it is worth pointing out that thermal insulation

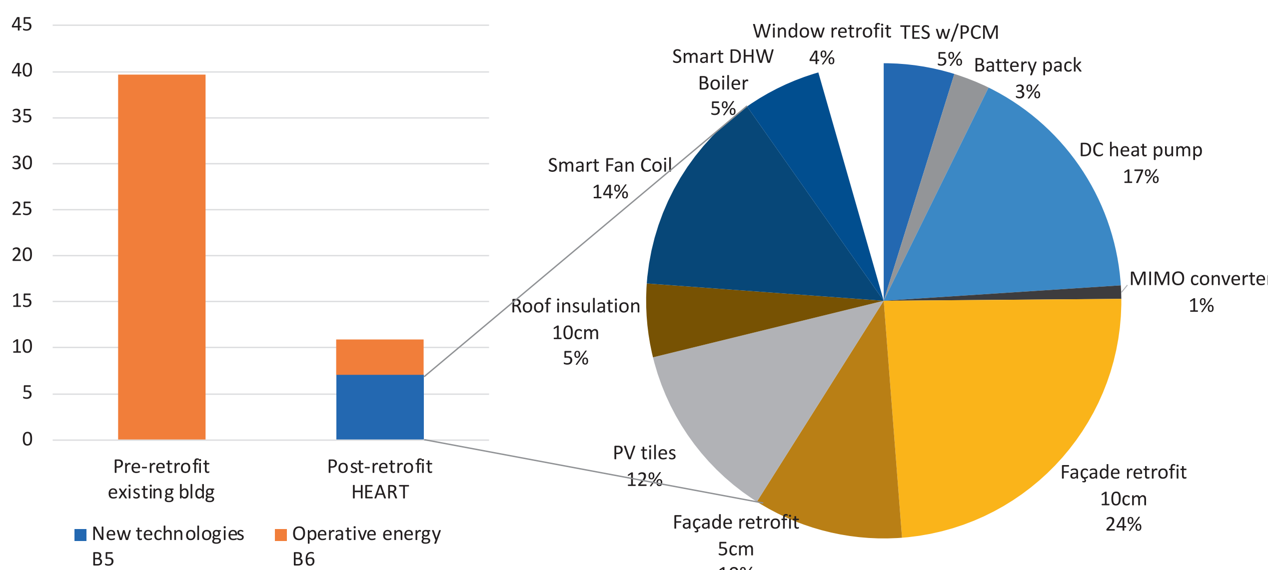

Fig. 5. GWP results in pre-retrofit and post-retrofit scenarios: on the left, per life cycle stages [$kgCO_2eq/m^2y$] and on the right per HEART technologies [%].

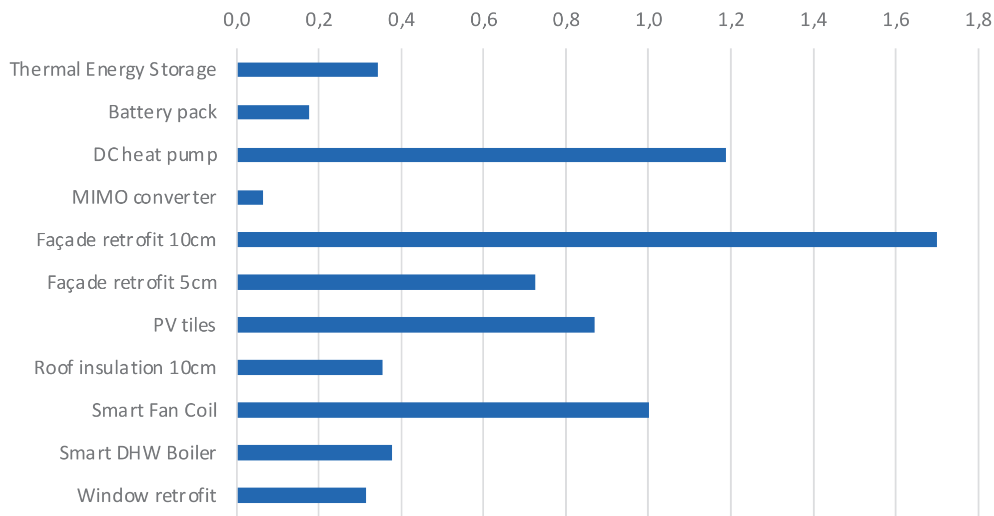

Fig. 7. GWP impacts of HEART technologies [$kgCO_2eq/m^2y$].

solutions for envelope retrofit, when grouped together and assessed at building level, turn out to be the most important GWP contributors, representing more than one third of the total carbon footprint (39 %). These construction technologies do not embody high carbon intensity, but the installation of large quantities for the building bring them at the spotlight (there is more than 1000 m^2 when summing up walls and roof areas). This prompts to reflect also in the unit of measurement required for LCA evaluations. Expressing GWP in $kgCO_2eq/m^2 \cdot y$ aligns with Green Building Rating Systems (e.g. LEED, BREEAM) and reference framework (e.g. Level(s)), as well with many building regulations which set benchmarks in this unit, making it essential to report impacts this way for compliance and for comparison purposes. However, the normalization for building size and lifetime must be kept in mind, since buildings vary significantly in size, floor area, and usage and consequently also the related environmental impacts.

4.2. Further LCA environmental indicators

While GWP is a critical indicator for assessing building environmental impacts, the one-dimensional focus may oversimplify the benefit of retrofit interventions. Including other LCA indicators ensures a holistic evaluation and balanced understanding, avoiding problem shifting and enabling better-informed decisions that minimize trade-offs and maximize sustainability across the building life cycle. This section presents therefore more completed LCA results for both the pre-retrofit (existing building) and post-retrofit (HEART technologies) scenarios, including the following six additional environmental indicators besides than GWP: Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Abiotic Depletion Potential for elements (ADP elem.), Abiotic Depletion Potential for fossil fuels (ADP fossil).

Table 4 presents a comprehensive comparison of the LCA environmental indicators under study between the pre-retrofit and post-retrofit scenarios, revealing significant reductions in environmental impact across several categories following the retrofitting process. As advertised, Global Warming Potential (GWP) decreases by 73 % compared to overall contributions, indicating a substantial mitigation of greenhouse gas emissions in post-retrofit scenario, thanks to the integration of HEART technologies in the building. Similarly, there are notable reductions in Photochemical Ozone Creation Potential (POCP) and Abiotic Depletion Potential for fossil fuels (ADP fossil) in which the reduction in energy consumption is not undermined by the new technologies, following the retrofitting interventions. They are attested at 76 % in POCP and 91 % in ADP fossil.

Table 4
Full building-level LCA results of pre-retrofit and post-retrofit scenarios [impacts/m^2y].

Environmental impact category	Unit	Pre-retrofit Existing building	Post-retrofit HEART
Global Warming Potential (GWP)	kg CO_2 eq/ m^2y	3.97E+01	1.09E+01
Ozone Depletion Potential (ODP)	kg CFC11 eq/m^2y	1.26E-06	4.90E-06
Acidification Potential (AP)	kg SO_2 eq/ m^2y	3.18E-02	4.86E+01
Eutrophication Potential (EP)	kg $(PO_4)_3$ eq/m^2y	1.03E-02	3.23E+01
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq/ m^2y	4.11E-03	9.70E-04
Abiotic Depletion Potential for elements (ADP elements)	kg Sb eq/ m^2y	6.94E-05	6.87E+01
Abiotic Depletion Potential for fossil fuels (ADP fossil)	MJ/m^2y	6.14E+02	5.27E+01

However, Acidification Potential (AP) and Eutrophication Potential (EP) increase in post-retrofit, with AP rising from 0.03 $kgSO_2eq/m^2y$ to 48.6 $kgSO_2eq/m^2y$ and EP increasing from 0.01 $kg(PO_4)_3eq/m^2y$ to 32.3 $kg(PO_4)_3eq/m^2y$. Similar growth trends in the environmental impacts are also observed for Ozone Depletion Potential (ODP) and Abiotic Depletion Potential for elements (ADP elem.). These increases are caused by the addition of new construction materials for retrofit, namely sandwich panels for façade, roof insulation and double-glazing for window, and of the set of building plant HEART technologies used in the retrofitting process. This highlights the importance of considering holistic environmental impacts, both operational and embodied, and employing sustainable practices throughout the retrofitting endeavor.

Overall, the table underscores the effectiveness of retrofitting interventions in mitigating certain environmental impacts, particularly in terms of greenhouse gas emissions and other few environmental indicators. Nevertheless, it also emphasizes the need for careful consideration of potential trade-offs to minimize adverse environmental consequences in other areas, since out of seven LCA indicators considered, four appear to worsen with the post-retrofit scenario.

More in detail, HEART retrofitting technologies include several components, ranging from advanced solutions like Thermal Energy Storage (TES) with Phase Change Material (PCM) spheres to traditional options such as roof insulation. Although they work synergistically as an integrated system, they embed different intensities of environmental impacts, explored specifically in Table 5. To enable a fast understanding, each technology performance is color-coded, according to the following: "green" indicates low environmental impact, "yellow" represents moderate impact and "red" signals high impact.

As already remarked in relation to GWP impacts, the most critical solutions across the multiple LCA indicators at issue are confirmed to be the façade retrofit package, DC heat pumps and smart fan coils. Because of the extensive use at building level, the façade insulation panels 10 cm thick show significantly high impacts in key areas, like Global Warming Potential (GWP), Acidification Potential (AP) and Abiotic Depletion Potential for fossil fuels (ADP fossil). Whereas both DC heat pump and smart fan coil contribute heavily to Ozone Depletion Potential (ODP), Eutrophication Potential (EP) and Abiotic Depletion Potential for elements (ADP elem.). In contrast, Photochemical Ozone Creation Potential (POCP) is driven by the impacts of PV tiles installed on the roof. Technologies like TES with PCM spheres, battery pack, roof insulation and window retrofit, namely the replacement of the existing single-glazing by new double-glazing, stand out for their consistently low environmental impacts across most environmental indicators.

These impact variations highlight the diverse environmental profiles of the technologies, underscoring the hotspots for each indicator to further improve the HEART toolkit for sustainable retrofitting. The goal is not to compare each other the different retrofit solutions, since intended as complementary measures for building energy efficiency, but rather of providing a valuable snapshot of the environmental trade-offs associated with each technology, revealing important challenges. For instance, certain technologies perform well in reducing greenhouse gas emissions but may exhibit higher impacts in other indicators. This is the case of the smart Domestic Hot Water (DHW) boiler that achieves relatively low GWP but contributes significantly to Ozone Depletion Potential (ODP), suggesting that focusing on one impact category can overlook broader environmental consequences. In accordance with the different environmental indicators, taken singly or in combination, the remaining technologies turn out to be priority or non-priority areas for design improvements to guarantee long-term sustainability of building retrofitting.

Overall, it is worth mentioning that the focus is here on the embodied impacts, lacking consideration of the operational savings these technologies may achieve individually over their lifetime. Indeed, operational impacts have been offered in the preceding paragraph in cumulative form, because of the proposed set of technologies co-exists and works in synergy. The GWP analysis in Fig. 4 attests the overall environmental benefits of post-retrofit compared to pre-retrofit scenario, by integrating both embodied and operational impacts. Furthermore, findings underscore the importance of considering environmental impacts comprehensively across different indicators when assessing the sustainability of building technologies. The results can inform decision-making processes aimed at promoting the adoption of environmentally responsible retrofit practices to mitigate their adverse environmental effects. Further research could explore strategies for improving the environmental performance of technologies, considering trade-offs between different impact categories and life cycle stages.

4.3. Environmental payback period

The LCA results confirm the effectiveness of the energy retrofitting strategies implemented in this case study in terms of reducing the environmental impacts of the building thanks to enhancing the operational energy performance of the building and optimum design of the HEART toolkit application and intervention scenarios. However, it is essential to consider the payback time associated with these interventions, as retrofit projects often involve upfront costs. In this case, payback time can be calculated by comparing the difference between total post-retrofit and total pre-retrofit values over time.

The GWP payback period can be determined as the time it takes for the cumulative reduction in emissions post-retrofit to offset the initial emissions associated with the pre-retrofit condition. Considering obtained results, it can be calculated that the total post-retrofit GWP starts to exceed the total pre-retrofit GWP from the fourth month onwards. This means that the retrofit intervention will recover the initial emissions associated with the pre-retrofit condition within the first year of operation under the post-retrofit scenario. Subsequently, any additional years of operation under the post-retrofit scenario will result in net emissions reductions compared to the pre-retrofit condition, contributing to overall environmental benefits over the building's lifecycle.

This underscores the effectiveness of the retrofit intervention in reducing greenhouse gas emissions and highlights the potential for long-term environmental sustainability.

5. Conclusion

As well know, the building sector holds a significant share in final energy consumption and greenhouse gas emissions globally, necessitating immediate actions to align with climate-neutral action plans. Despite efforts to reduce energy consumption in new buildings, a large portion of the existing building stock remains outdated, posing challenges for construction decarbonization. In response, the European Union (EU) has proposed ambitious targets for reducing greenhouse gas emissions, including severe requirements for energy efficiency in buildings and increased renovation rates. The awareness that the focus on operational energy performance alone may shift the environmental burden towards embodied impacts associated with building materials and components is now widespread and pushed by EU building policies. To this end, Life Cycle Assessment (LCA) emerged as crucial for evaluating building sustainability in a scientific way, resulting at the core of Level(s) framework and increasingly demanded within Green Building Rating Systems (GBRSs).

Level(s) incorporates a full life-cycle assessment approach, providing a common language for sustainability assessment across Europe and enabling the quantitative assessment of environmental impacts across the building life cycle. In practical applications, however, challenges such as complexity, data requirements, system boundary and lack of benchmarks have been recorded. Shared recommendations for improvement include simplifying user guides, providing national

Table 5
Full building-level LCA results of HEART technologies for retrofit [impacts/m^{2}y].

Technologies	GWP [kg CO2 eq]	ODP [kg CFC11 eq]	AP [kg SO2 eq]	EP [kg PO4 eq]	POCP [kg C2H4 eq]	ADP elem. [kg Sb eq]	ADP fossil [MJ]
Thermal Energy Storage	3.42E-01	4.22E-08	1.09E+00	2.07E+00	4.22E-08	1.88E-05	4.95E+00
Battery pack	1.76E-01	9.65E-09	4.51E-01	2.40E-01	9.65E-09	1.04E-05	1.84E+00
DC heat pump	1.19E+00	1.29E-06	1.11E+01	8.66E+00	1.29E-06	5.41E-05	4.32E+00
MIMO converter	6.44E-02	4.64E-09	1.27E+00	1.04E+00	4.64E-09	1.35E-05	7.41E-01
Façade panels 10 cm	1.70E+00	1.43E-07	1.42E+01	5.88E+00	1.43E-07	3.44E-05	2.30E+01
Façade panels 5 cm	7.25E-01	5.40E-08	7.52E+00	2.86E+00	5.40E-08	1.67E-05	9.37E+00
PV tiles	8.68E-01	5.92E-08	3.85E-03	1.90E-03	1.78E-04	2.61E-05	1.00E+01
Roof insulation 10 cm	3.55E-01	3.82E-08	−1.25E-01	8.17E-01	3.82E-08	2.00E-06	5.12E+00
Smart Fan Coils	1.00E+00	2.33E-06	1.16E+01	9.20E+00	2.33E-06	5.16E-05	3.31E+00
Smart DHW Boilers	3.78E-01	8.25E-07	1.20E+00	1.18E+00	8.25E-07	6.76E-06	1.76E+00
Window retrofit	3.16E-01	4.04E-08	2.80E-01	3.50E-01	4.04E-08	4.34E-06	4.28E+00

benchmarks and enhancing user-friendly tools, emphasizing the comprehensiveness, robustness and operability of the adopted LCA tools and databases, as well the need for digitalization approaches like Building Information Modeling (BIM).

In this context, the paper contributes to the understanding of holistic sustainability assessment in building energy retrofit projects, serving as a reference for future endeavors in the field. Indeed, the LCA results demonstrate the significant improvements in environmental performance following energy retrofitting interventions in buildings, with crucial implications for both the environmental sustainability and economic viability of retrofit projects. Firstly, the 73 % reduction of total GWP impacts is a significant achievement, particularly in demonstrating the potential of retrofit solutions like HEART technologies to enhance energy efficiency and reduce emissions. The pre-retrofit building has exhibited high levels of energy consumption and thus environmental impacts, while the post-retrofit building demonstrated marked improvements in terms of environmental burdens, thanks to notably lower energy consumption (−90 % GWP of operating energy impacts), due to the integration of the new technologies. These findings underscore the effectiveness of energy-efficient technologies and practices in enhancing the life cycle sustainability of buildings and reducing their environmental footprint.

Moreover, the results highlight the importance of considering holistic environmental impacts when evaluating retrofit interventions. While impacts abatements have been observed in several environmental indicators beyond Global Warming Potential (GWP), like in Photochemical Ozone Creation Potential (POCP) and Abiotic Depletion Potential for fossil fuels (ADP fossil), increases have been noted in others, such as Acidification Potential (AP) and Eutrophication Potential (EP). This underscores the need for proper consideration of potential trade-offs and the adoption of sustainable practices throughout the retrofitting process, but even over the building life cycle, to minimize adverse environmental effects.

Insights are also provided into the distribution of environmental impacts among the different technologies integrated for building retrofitting. The prefabricated insulation panel system, extensively applied on the façades, and the heating/cooling systems, chiefly DC heat pump and smart fan coil, are found to have high priority in terms of environmental impacts, highlighting the need for targeted interventions to reduce the embodied emissions associated with these components. Giving the impact share and the building-scale extension, the possible mitigation strategies prioritize the inclusion of alternative materials for façade sandwich panels, by shifting in the next future from fossil-based insulation to bio-based insulation foam and integrating low-impact coat steel layers. Going into more detail, in the insulating core usually composed of polyurethane foam, special attention must be paid to isocyanate, finding and incorporating in industrial production climate neutral solutions for isocyanate. Instead, for external layers, the focus shift to the energy-intensive galvanizing process, by reducing reliance on petrochemicals during the coating process for decreasing the related environmental impacts. Regarding DC heat pump and smart fan coil, the impact hotspots analysis at product-level emphases the role of specific electronic units as well as the set of metallic components, calling for worth consideration of local the supply chain and the evidence of recycled contents. Additionally, photovoltaic tiles turn out to contribute substantially to the carbon footprint, suggesting opportunities for improving the solar cell manufacturing processes and circular economy-based approach to mitigate their environmental impact. The work therefore highlights the commitment to technological research to be pursued on several fronts, demonstrating from the outset that the increase in embodied emissions is largely offset by the CO_2 savings in the operational phase, considering that the overall payback time is less than one year.

Given the global attention captured by building stock renovation at international scale, future research is called to further explore specific retrofit measures and technologies aimed at maximizing energy efficiency while minimizing environmental impacts, based on the presented LCA results and hotspots. Suggestions for improvement include in particular the assessment of project GWP reductions under varying grid carbon intensities to validate long-term results. Indeed, the work demonstrates the effectiveness of the retrofit reducing operational emissions, but heavily relying on the current energy grid, which however evolve over time. A scenario analysis incorporating future decarbonization of energy sources would provide a more comprehensive outlook. In addition, the analysis would benefit from a full-LCA study, considering a reference study period (e.g. 50 years according to Level(s) framework) to include maintenance, replacement and end-of-life modules and to ensure net-positive outcomes, aligned with broader sustainability goals towards circular economy. The run of a complete LCA, covering the entire life cycle, will be of added value only when manufacturers will be interested not only in the production business but also in their product management over time, in order to evaluate their feasibility and effectiveness in the long term. The work thus addresses some critical points that ultimately attracted the attention of industry, supporting the definition of the environmental footprint of retrofit projects, by providing an holistic assessment of both building elements and technical equipment, in compliance with Level(s) framework and the recast EPBD.

The results of the study are indeed expected to become a valuable reference for the building sector due to several compelling factors. By employing the LCA method in compliance with Level(s) framework and ISO/EN standards, they ensure consistency and representativeness. The use of real building as case study adds significant practical relevance and forthcoming chance to monitor the related environmental performance over time. Rather than relying on theoretical models, the work delivers tangible insights into the environmental impacts of smart energy retrofitting, addressing a critical area of focus as the built environment transitions toward energy efficiency and decarbonization. This real-world application makes the findings directly useful for practitioners, policymakers, researchers and all relevant stakeholders, by ensuring and stressing the importance of the environmental optimization in the process of technological evolution of the built environment.

Furthermore, the study alignment with the Level(s) framework enhances its compatibility with emerging sustainability policies, resonating with current strategic priorities and contributing to the LCA benchmarking of retrofit project. This is crucial for a double purpose. On one hand, to help populating the reference sample underlying the definition of benchmarks. On the other, to support practical application, allowing results comparison based on reference values or performance scale and driving the adoption of best practices. By generating measurable outcomes, namely LCA-based environmental performance and environmental payback period, as well as embodied impacts reductions and energy efficiency improvements compared to pre-retrofit scenario, the presented evidence-based insights can guide future retrofitting project towards sustainable practice, opening up new frontiers to be explored by including all relevant stakeholders.

CRediT authorship contribution statement

Anna Dalla Valle: Writing – review & editing, Software, Investigation, Data curation, Conceptualization. **Hashem Amini Toosi:** Writing – original draft, Software, Conceptualization. **Fabrizio Leonforte:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Claudio Del Pero:** Writing – review & editing, Project administration, Formal analysis, Conceptualization. **Monica Lavagna:** Writing – review & editing, Supervision. **Andrea Campioli:** Supervision, Methodology. **Niccolò Aste:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fabrizio Leonforte reports was provided by Polytechnic University of Milan. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study and project are financially supported by EU Research and Innovation programme Horizon 2020 through number 768921 – HEART.

Data availability

Data will be made available on request.

References

[1] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, "Building decarbonization: Assessing the potential of building-integrated photovoltaics and thermal energy storage systems," *Energy Reports*, vol. 8, pp. 574–581, Dec. 2022, doi: 10.1016/J.EGYR.2022.10.322.

[2] I.N. Enwo-Irem, C. Urom, Climate change concerns and macroeconomic condition predictability, Financ. Res. Lett. 60 (Feb. 2024) 104903, https://doi.org/10.1016/J.FRL.2023.104903.

[3] J. Falana, R. Osei-Kyei, V.W. Tam, Towards achieving a net zero carbon building: A review of key stakeholders and their roles in net zero carbon building whole life cycle, J. Build. Eng. 82 (Apr. 2024) 108223, https://doi.org/10.1016/J.JOBE.2023.108223.

[4] European Commission, "Renovation Wave," 2020. https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1835 (accessed Feb. 08, 2024).

[5] European Commission, "The European Green Deal - European Commission," 2024. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed Jan. 30, 2024).

[6] "Energy Performance of Buildings Directive." https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed Feb. 08, 2024).

[7] European Commission, "Renovation and decarbonisation of buildings," 2021. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683 (accessed Feb. 08, 2024).

[8] European Commission, "Delivering the European Green Deal - European Commission," 2021. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#renovating-buildings-for-greener-lifestyles (accessed Feb. 08, 2024).

[9] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, "Implementing Life Cycle Sustainability Assessment in Building and Energy Retrofit Design—An Investigation into Challenges and Opportunities," pp. 103–136, 2021, doi: 10.1007/978-981-16-4562-4_6.

[10] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, "Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review," *Sustainable Cities and Society*, vol. 60. Elsevier Ltd, p. 102248, 2020, doi: 10.1016/j.scs.2020.102248.

[11] ISO-14040, "ISO 14040-Environmental management – Life cycle assessment – Principles and framework," 2006.

[12] ISO-14044, "ISO 14044-Environmental management – Life cycle assessment – Requirements and guidelines," 2006.

[13] EN_15978, "EN 15978:2011, Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method," 2011.

[14] B. S. I, "BS EN 15804:2012 +A1:2013 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products," no. February, 2014.

[15] M. Shan and B. gang Hwang, "Green building rating systems: Global reviews of practices and research efforts," *Sustain. Cities Soc.*, vol. 39, no. October 2017, pp. 172–180, 2018, doi: 10.1016/j.scs.2018.02.034.

[16] D.T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey, A critical comparison of green building rating systems, Build. Environ. 123 (Oct. 2017) 243–260, https://doi.org/10.1016/J.BUILDENV.2017.07.007.

[17] B. Mattoni, C. Guattari, L. Evangelisti, F. Bisegna, P. Gori, and F. Asdrubali, "Critical review and methodological approach to evaluate the differences among international green building rating tools," *Renew. Sustain. Energy Rev.*, vol. 82, no. October 2017, pp. 950–960, 2018, doi: 10.1016/j.rser.2017.09.105.

[18] T. Sartori, R. Drogemuller, S. Omrani, F. Lamari, A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS), J. Build. Eng. 38 (Jun. 2021), https://doi.org/10.1016/j.jobe.2021.102180.

[19] O. Suzer, A comparative review of environmental concern prioritization: LEED vs other major certification systems, J. Environ. Manage. 154 (May 2015) 266–283, https://doi.org/10.1016/J.JENVMAN.2015.02.029.

[20] W.O. Collinge, et al., Integrating Life Cycle Assessment with Green Building and Product Rating Systems: North American Perspective, Procedia Eng. 118 (Jan. 2015) 662–669, https://doi.org/10.1016/J.PROENG.2015.08.500.

[21] H. Dekkiche, A. Taileb, The Importance of Integrating LCA into the LEED Rating System, Procedia Eng. 145 (Jan. 2016) 844–851, https://doi.org/10.1016/J.PROENG.2016.04.110.

[22] N. Dodd and S. Donatello, "Level(s)-A common EU framework of core sustainability indicators for office and residential buildings User manual 2: Setting up a project to use the Level(s) common framework (Publication version 1.1)," 2021. [Online]. Available: https://ec.europa.eu/jrc.

[23] HEART, "The Holistic Energy and Architectural Retrofit Toolkit (HEART)," *https://heartproject.eu/*. 2022, [Online]. Available: https://heartproject.eu/.

[24] "The Level(s) Calculation and Assessment Tool (CAT) - Publications Office of the EU." https://op.europa.eu/en/publication-detail/-/publication/fc6e47c7-e21c-11ec-a534-01aa75ed71a1 (accessed Mar. 11, 2024).

[25] C. Díaz-López, M. Carpio, M. Martín-Morales, M. Zamorano, Defining strategies to adopt Level(s) for bringing buildings into the circular economy. A case study of Spain, J. Clean. Prod. 287 (Mar. 2021) 125048, https://doi.org/10.1016/J.JCLEPRO.2020.125048.

[26] H. ; Birgisdottir and K. Haugbølle, "Aalborg Universitet Evaluation of Level(s) Lessons learned from 18 Danish examples," 2019, Accessed: Feb. 08, 2024. [Online]. Available: https://sbi.dk/Assets/Evaluation-of-Level-s/SBi-2019-11.pdf.

[27] J. Venäläinen, M. Kuittinen, E. Huttunen, and S. le Roux, "Level(s) – test report from Finland," Sep. 2019, Accessed: Feb. 08, 2024. [Online]. Available: https://julkaisut.valtioneuvosto.fi/handle/10024/161783.

[28] M. Honic, C. De Wolf, Applying EU Level(s) framework indicators to improve circularity: A case study, IOP Conf. Ser. Earth Environ. Sci. 1196 (1) (Jun. 2023) 012041, https://doi.org/10.1088/1755-1315/1196/1/012041.

[29] D. Ramon, C. Pironnet, K. Allacker, Sustainability assessment of a Flemish office building with Level(s): a Level 1 assessment, IOP Conf. Ser. Earth Environ. Sci. 323 (1) (Aug. 2019) 012041, https://doi.org/10.1088/1755-1315/323/1/012041.

[30] J. Miguel and S. Silva, "Level(S) in action: an exploratory study of eu's sustainability assessment framework on a portuguese social housing project," Accessed: Feb. 08, 2024. [Online]. Available: http://www.fe.up.pt.

[31] B. do N. Lopes, "Level(s) framework for residential buildings assessment in Portugal: Use stage energy performance and life cycle global warming potential," *Level(s) Framew. Resid. Build. Assess. Port. Use stage energy Perform. life cycle Glob. Warm. potential*, Nov. 2023, Accessed: Feb. 08, 2024. [Online]. Available: https://estudogeral.uc.pt/handle/10316/110602.

[32] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, "Towards Sustainability Assessment of the Built Environment: A Classification of the Existing Challenges," *Sustainability*, vol. 15, no. 15, p. 12055, Aug. 2023, doi: 10.3390/su151512055.

[33] M. Elias, "Sustainability Performance Assessment for Buildings throughout their Life Cycle using the EU Level(s) Framework," 2023, Accessed: Feb. 08, 2024. [Online]. Available: http://www.theseus.fi/handle/10024/807717.

[34] A. S. Cordero, S. G. Melgar, and J. M. A. Márquez, "Green Building Rating Systems and the New Framework Level(s): A Critical Review of Sustainability Certification within Europe," *Energies 2020, Vol. 13, Page 66*, vol. 13, no. 1, p. 66, Dec. 2019, doi: 10.3390/EN13010066.

[35] M. Santos, V. Lohmann, C. Ferreira, P. L. Gaspar, and C. Horta, "Assessing Carbon Neutrality in Buildings: Comparison of Green Building Rating Systems Based on Their Alignment with Level(S) Framework." Accessed: Feb. 08, 2024. [Online]. Available: https://papers.ssrn.com/abstract=4259806.

[36] S. Ferrari, M. Zoghi, T. Blázquez, and G. Dall'O, "New Level(s) framework: Assessing the affinity between the main international Green Building Rating Systems and the european scheme," *Renew. Sustain. Energy Rev.*, vol. 155, p. 111924, Mar. 2022, doi: 10.1016/J.RSER.2021.111924.

[37] C. De Wolf, M. Cordella, N. Dodd, B. Byers, S. Donatello, Whole life cycle environmental impact assessment of buildings: Developing software tool and database support for the EU framework Level(s), Resour. Conserv. Recycl. 188 (Jan. 2023) 106642, https://doi.org/10.1016/J.RESCONREC.2022.106642.

[38] P. Del Rosario, E. Palumbo, and M. Traverso, "Environmental Product Declarations as Data Source for the Environmental Assessment of Buildings in the Context of Level(s) and DGNB: How Feasible Is Their Adoption?," *Sustain. 2021, Vol. 13, Page 6143*, vol. 13, no. 11, p. 6143, May 2021, doi: 10.3390/SU13116143.

[39] E. Palumbo, B. Soust-Verdaguer, C. Llatas, and M. Traverso, "Implications of the building system boundary definition to conduct an LCA. A case study comparison of two frameworks for assessing building sustainability: DGNB and Level(s)," *E3S Web Conf.*, vol. 349, p. 04015, May 2022, doi: 10.1051/E3SCONF/202234904015.

[40] M. Erlandsson, J. S. Lundin, and N. Leveau, "Evaluation of the European assessment method Level(s) for buildings," 2019, Accessed: Feb. 08, 2024. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-125.

[41] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (9) (Sep. 2016) 1218–1230, https://doi.org/10.1007/S11367-016-1087-8/FIGURES/7.

[42] A. Dalla Valle, "Change management towards Life Cycle AE(C) practice", Springerbriefs in Applied Sciences and Technology, Springer, Cham, 2021, pp. 1–127.