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IT report on definition of decarbonization pathways and suitable design strategies

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Executive summary

This report presents the national assessment of decarbonisation pathways, suitable design strategies and Whole Life Carbon (WLC) reduction targets developed for the Italian building context within the **INDICATE LIFE** project.

The activity was led by UNIBG and developed with contributions from the Italian Consortium partners.

Building upon the national baseline assessment and hotspot analysis developed in the previous national deliverables, the analysis identifies, structures and assesses a set of decarbonisation actions aimed at reducing WLC across the main life-cycle stages of buildings.

An integrated methodological framework was developed, combining the **Avoid-Shift-Improve (ASI)** approach with the LCM structure adopted in the LCA assessment.

The conceptualisation and development of a dedicated WLC measures matrix represent a key methodological contribution of the deliverable, translating this combined structure into a hierarchical structure composed of **pathways**, **strategy packages**, **WLC strategies** and **WLC measures**.

The resulting matrix links broad decarbonisation objectives to specific actions that can be analysed within the scope of the INDICATE LIFE project.

Building on this methodological structure, the assessment combines the review of European policy developments, scientific literature and national industrial practices with the analysis of selected **WLC measures**. Measures were classified according to their relevance, data availability, technical feasibility and compatibility with the available datasets.

This methodological framework also defines the criteria for selecting the measures to be assessed and, where quantitative assessment is possible, the representative case studies considered suitable for remodelling.

Where possible, measures were assessed quantitatively through the **remodelling** of **representative case studies** selected from the Italian INDICATE LIFE dataset. Other measures were discussed qualitatively, in relation to their applicability, methodological limitations and potential contribution to WLC reduction.

The results show that the reduction potential is unevenly distributed across life-cycle stages and building typologies. Modules **A1-A3** emerge as a key area for WLC reduction, confirming the central role of material and construction product production. Measures addressing the decarbonisation of production processes, the use of materials with higher recycled content and carbon capture technologies show relevant effects in this stage. Module **B6** plays a different role depending on the building typology: office buildings show higher sensitivity to operational energy decarbonisation measures, while residential typologies remain largely dominated by Embodied Carbon. Measures acting on transport and end-of-life stages show lower absolute reductions, but remain relevant when considered as part of integrated decarbonisation scenarios.

The aggregation of results according to the **ASI framework** indicates that the **Improve** pathway achieves the highest quantified reduction among the measures modelled. This result should not be interpreted as an intrinsic superiority of Improve over Avoid or Shift, but rather as a reflection of the greater methodological maturity and data availability for measures based on improvements in materials, production processes, transport systems and energy sources. The **Avoid** pathway also provides a relevant contribution, particularly through measures related to durability,

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maintenance and circular material use. The **Shift** pathway was not quantitatively assessed in this study due to methodological limitations associated with the direct substitution of conventional materials with bio-based alternatives in the available case studies.

The analysis of combinations between WLC measures shows that the overall reduction potential cannot be calculated as the simple sum of individual measure benefits. Interactions between measures may generate synergies, overlaps or potential double-counting effects. For this reason, a compatibility matrix was developed to identify which combinations can be applied, which require caution and which are methodologically not applicable. The combined application of selected measures shows an overall reduction potential of approximately **27%** for SFH, **25%** for MFH and **31%** for office buildings. The target values proposed in this report should be understood as indicative reduction values relative to the baseline, mainly expressed as percentage reductions. They are not intended as regulatory thresholds or directly applicable limit values. Rather, they provide an initial evidence-based reference for describing the WLC reduction potential achievable through selected decarbonisation strategies in the Italian building context.

Overall, the methodological framework provides an integrated basis for linking national baseline hotspots, decarbonisation pathways and strategies, design measures, case-study remodelling and **measurable WLC reduction targets**. The findings support the identification of the life-cycle stages and intervention categories with the **highest reduction potential** and can inform **future benchmarking activities**, **progressive reduction trajectories,** and the development of policy, procurement or voluntary certification tools aimed at reducing the Whole Life Carbon of buildings in Italy.

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Acronyms

AIPE	Italian Association of Expanded Polystyrene
ASI	Avoid-Shift-Improve
BOF	Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CDR	Carbon Dioxide Removal
CRS	Circular Reduction Strategies
D	Deliverable
DAC	Direct Air Capture
EAF	Electric Arc Furnace
EC	Embodied Carbon
EDU	Educational
EF	Emission Factor
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPD	Environmental Product Declaration
EU	Europe Union
GBC Italia	Italy Green Building Council
GFA	Gross Floor Area
GWP	Global Warming Potential
HFA	Heated Floor Area
HOS	Hospitality
HVAC	Heating, Ventilation and Air Conditioning
KU Leuven	Katholieke Universiteit Leuven

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LCA	Life Cycle Assessment
LCM	Life Cycle Module
LWS	Living Wall System
MFH	Multy Family House
OC	Operational Carbon
OFF	Office
PNIEC	Italian National Integrated Energy and Climate Plan
POLIMI	Politecnico di Milano
POLITO	Politecnico di Torino
RC	Recycled Content
RES	Renewable Energy Source
RSP	Reference Study Period
SFH	Single Family House
SL	Service Life
UNIBG	Università degli Studi di Bergamo
WLC	Whole Life Carbon
WP	Work Package
WorldGBC	World Green Building Council
XTR	Non-Residential Buildings

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1. Introduction

1.1. Purpose and scope

Within the framework of the **INDICATE LIFE** project activities, report **D7.23 – IT report on definition of decarbonization pathways and suitable design strategies** develops the Italian contribution to the definition of decarbonisation pathways, suitable design strategies and **Whole Life Carbon** reduction targets. The work builds on the national baseline assessment and hotspot analysis presented in **D7.22**, and develops a structured framework of decarbonisation actions applicable to the Italian building context, which are subsequently selected and assessed in relation to their potential contribution to WLC reduction across the main life-cycle stages of buildings.

An integrated methodological framework was developed by combining the **Avoid–Shift–Improve (ASI)** approach with the LCM structure adopted in the **LCA** assessment.

This methodological integration is a key feature of the deliverable and provides the basis for organising decarbonisation actions within a hierarchical structure composed of **pathways**, **strategy packages**, **WLC strategies** and **WLC measures**, linking broad decarbonisation objectives to specific actions that can be analysed within the scope of the Italian case studies.

The analysis combines a review of European policies, scientific literature and national industrial practices with the assessment of selected decarbonisation measures. The objective is to identify technically feasible and representative measures for the Italian context, define their methodological implementation, quantify their contribution to WLC reduction where possible, and provide the basis for the definition of national WLC targets.

For each measure, the most appropriate assessment approach is selected according to its relevance, data availability and analytical feasibility. Where quantitative assessment is applicable, representative case studies are selected for remodelling.

Quantitative measures are assessed through the remodelling of selected representative case studies, in order to estimate their reduction potential compared with the baseline and identify the LCMs where their effects are concentrated. Qualitative measures are instead discussed in relation to their relevance, applicability and methodological limitations within the Italian building context.

The report is organised into eight chapters. Following this introductory chapter, **Chapter 2** describes the **methodological approach** adopted for the development of the decarbonisation pathways and WLC measures. **Chapters 3 and 4** present the **selection** of the decarbonisation pathways and the corresponding design strategies. **Chapter 5** describes the **methodological implementation** of the selected WLC strategies, while **Chapter 6** presents and discusses the quantitative assessment **results**. Based on these results, **Chapter 7** defines the national **WLC targets** and proposes combinations of WLC measures to support future decarbonisation studies. Finally, **Chapter 8** summarises the main findings of the study, discusses limitations and future developments, and presents the overall conclusions.

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2. Description of the approach taken for the definition of the pathways

The **methodological framework** consists of three sequential steps, each comprising a series of interconnected activities (Figure 1), providing a consistent and transparent methodology for defining, assessing, and setting targets for WLC decarbonisation strategies.

The definition of the **decarbonisation pathways** combines the findings of the Italian hotspot analysis presented in **D7.22** (Lavagna et al., 2026) with the decarbonisation pathway structure proposed in the *Support study for the development of the roadmap for the reduction of Whole Life Carbon of Buildings* commissioned by the European Commission's Directorate-General for Environment (DG ENV), (Le Den et al., 2023). The hotspot analysis was used to identify the life cycle stages, building elements, and construction materials contributing most significantly to WLC emissions in representative Italian case studies, while the pathway structure proposed by Le Den et al. (2023) provides the reference for organising decarbonisation actions. Within D7.23, these elements are integrated with the LCM structure adopted in the national LCA assessment and translated into a hierarchical organisation comprising **pathways**, **strategy packages**, **WLC strategies** and **WLC measures**. Starting from this integration, , the pathways were adapted to the Italian context through the selection and organisation of design strategies and WLC measures that address the main Whole Life Carbon hotspots identified in the national analysis while reflecting the characteristics of the Italian building stock and construction practices.
The broad decarbonisation pathways retain the Avoid–Shift–Improve structure adopted in the Ramboll reference. Their operationalisation for the Italian context was developed through the selection, adaptation and organisation of the associated design strategies and WLC measures, taking into account the results of the national hotspot analysis, the characteristics of the Italian building stock, and, where available, Italian construction practices. Where representative national data were unavailable, scientific and technical literature from the European context was used to support the definition and assessment of the pathways and associated measures.

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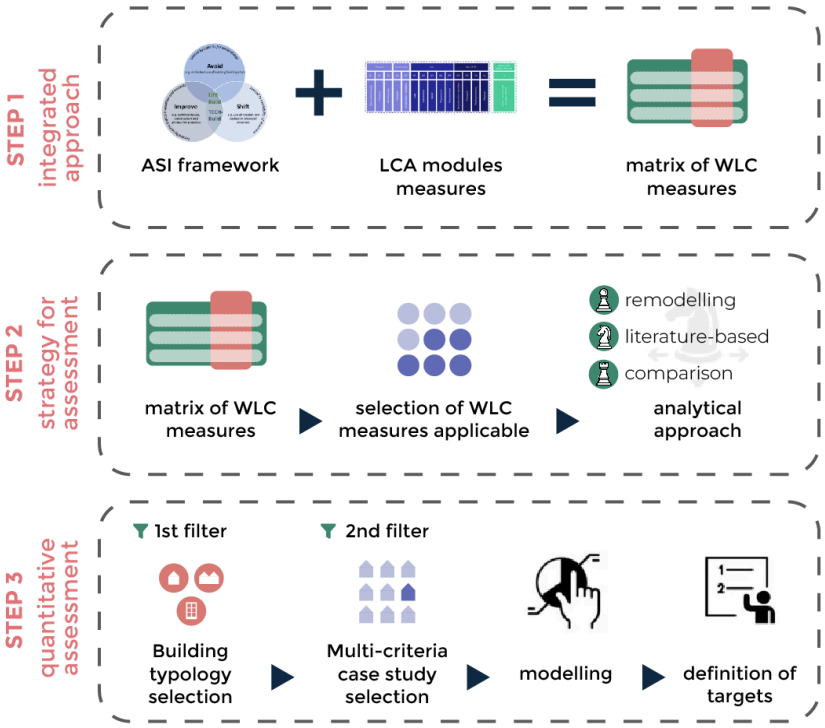


Figure 1: ***Methodological framework for the development and quantitative assessment of WLC decarbonisation strategies***

The **hierarchical level-scaled approach** proposed in the Ramboll framework was adopted as the reference structure for organising WLC measures (Le Den et al., 2023). This framework is based on the ASI approach, which groups decarbonisation actions into three complementary pathways (Figure 2):

- **Avoid**, aimed at reducing the demand for new construction by maximising the use of the existing building stock;
- **Shift**, focused on replacing conventional materials and resources with low-carbon alternatives;
- **Improve**, dedicated to the optimisation of design, construction, and manufacturing processes.

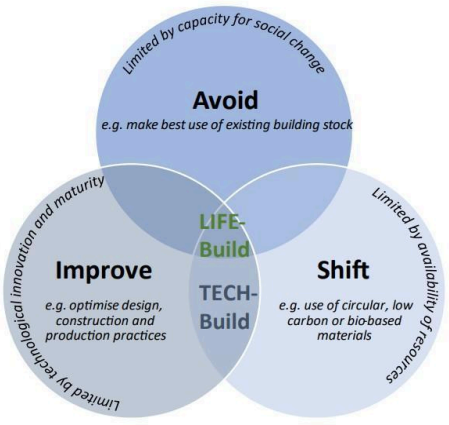


Figure 2: Avoid–Shift–Improve (ASI) framework for WLC decarbonisation. Source: Le Den et al. (2023)

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2.1. Development of the WLC Measures Matrix

The **first step** (Figure 3) constitutes the methodological basis for the analyses presented in Chapter 2.2. The methodological approach proposed in this study integrates ASI pathways with WLC measures associated with the relevant LCA modules, providing the methodological basis for developing the **WLC measures matrix** (Figure 5).

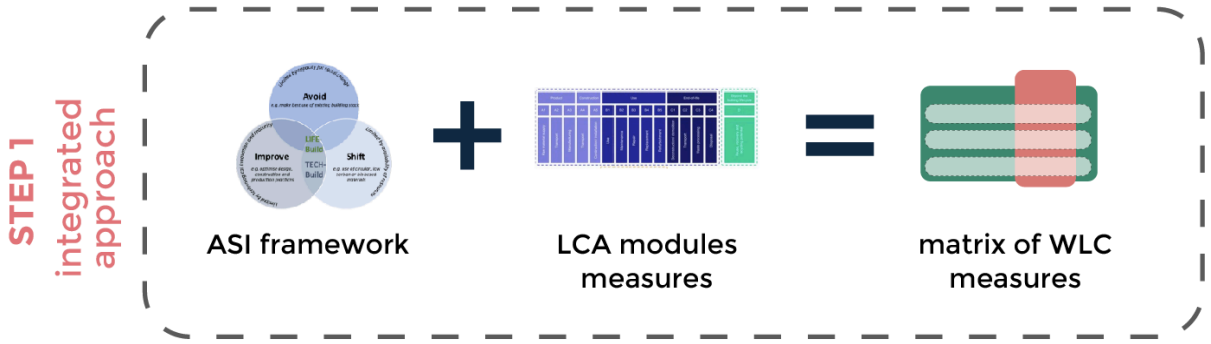


Figure 3: Integration of the ASI framework and LCA modules for the development of the WLC measures matrix

The framework defines a descending hierarchy of decarbonisation actions, structured into pathways, strategy packages, design strategies, and individual WLC measures (Figure 4). This **hierarchical organisation** enables each measure to be positioned within a broader strategic context, rather than being considered as an isolated intervention.

Each pathway (e.g., Avoid) is subdivided into strategy packages (e.g., Increase circularity and use of existing buildings), which are further articulated into design strategies (e.g., Increase circular material use). Each design strategy is translated into one or more WLC measures (e.g., use materials with high recycled content), representing specific actions that can subsequently be modelled and assessed within the national case studies.

This hierarchical organisation enables each measure to be positioned within a broader strategic framework while preserving the relationship between strategic objectives and operational interventions.

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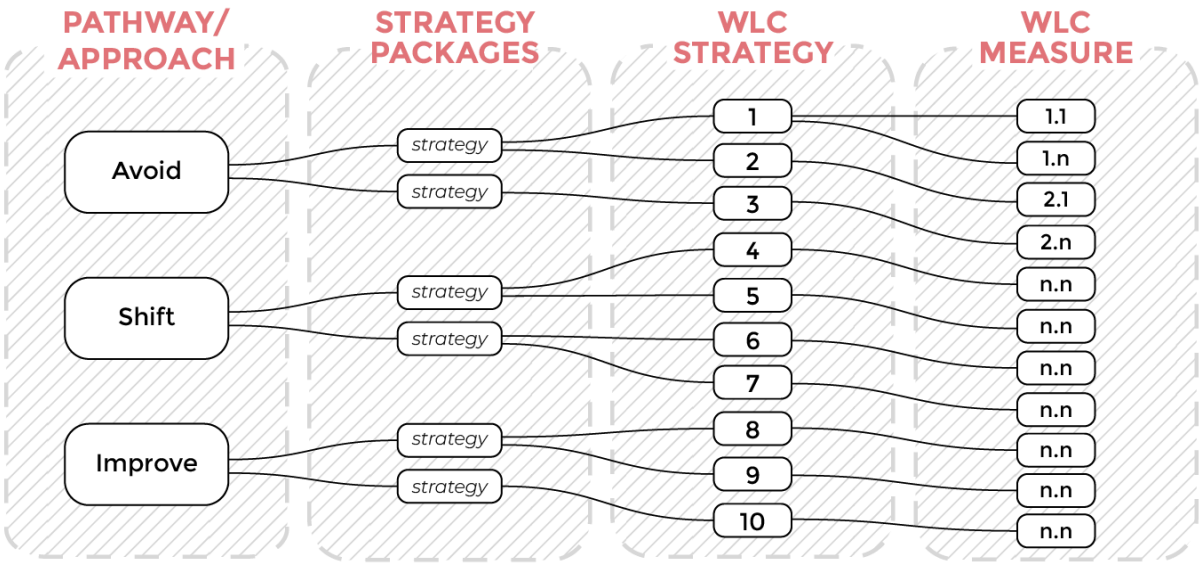


Figure 4: Hierarchical organisation of the WLC decarbonisation framework

This horizontal approach is complemented by a **vertical perspective** based on the life cycle modules (LCMs) defined by the EN 15978 framework. Each WLC strategy is therefore analysed across the different LCMs, allowing each measure to be associated with the specific temporal and functional context in which it is implemented.

The combination of these two perspectives (horizontal, by strategic pathway, and vertical, by LCM) results in a positioning matrix of WLC measures (Figure 5).

Within this matrix, each measure is positioned at the intersection of its reference pathway and the corresponding LCM, providing an immediate overview of how measures are distributed across life cycle stages and strategic pathways. The matrix, therefore, serves as a methodological framework that supports the analytical choices made in the subsequent phases of the study.

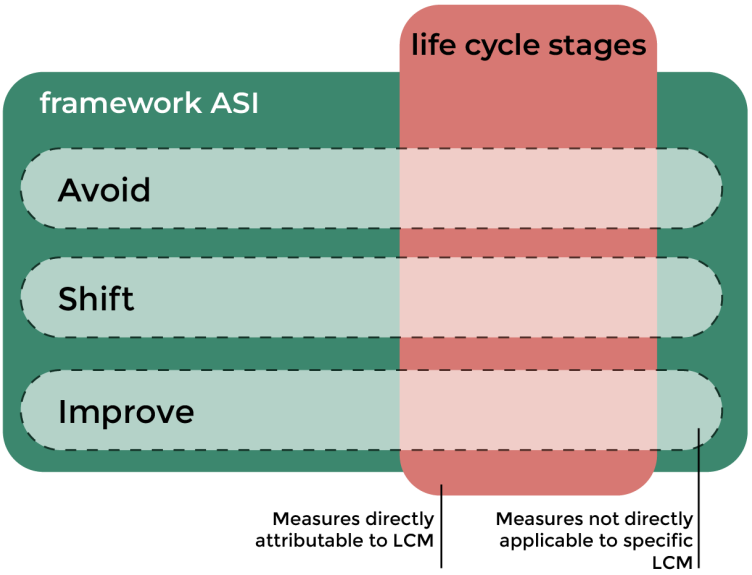


Figure 5: Positioning matrix of WLC measures according to the ASI framework and life cycle stages

This integrated approach enables each analysed measure to be positioned within the WLC measures matrix according to both the relevant LCM and the corresponding

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decarbonisation pathway. The resulting positioning supports a **systematic organisation** of WLC reduction strategies and facilitates the identification of additional measures and their integration into the proposed methodology. Once integrated with the quantitative assessment, the WLC measures matrix enables identification of the LCMs with the greatest decarbonisation potential, providing operational guidance for prioritising future emission-reduction actions.

2.2. Selection and Assessment of WLC Measures

The **second step** (Figure 6), which constitutes the methodological basis for the analyses presented in Chapters 3 and 4, concerns the **selection** of the WLC measures to be analysed and the definition of the most appropriate **analytical approach** for each.

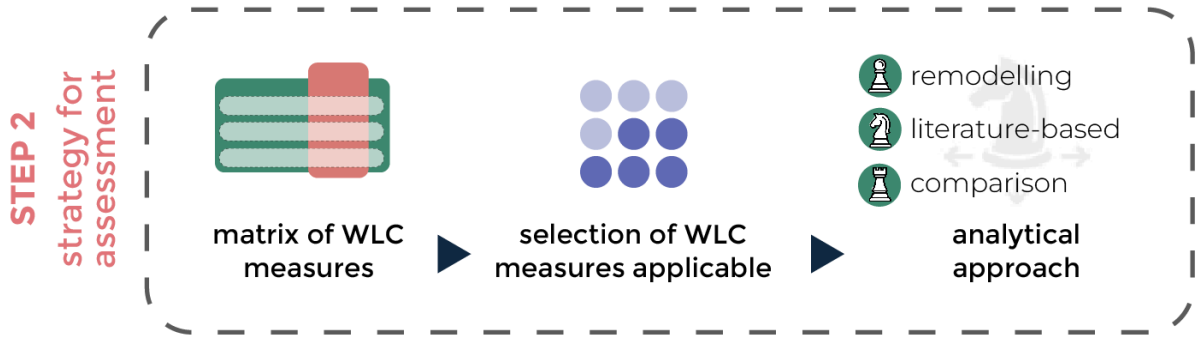


Figure 6: Methodological workflow for the selection of WLC measures and the definition of the corresponding analytical approaches

Drawing on the WLC measures matrix developed in Step 1, the measures are evaluated according to their strategic relevance, data availability, and analytical feasibility within the specific context and their applicability to the INDICATE LIFE IT project.
For each selected WLC measure, the most appropriate **analytical approach** is identified based on its characteristics and available information. The methodological framework includes three complementary analytical approaches:

- **Case study remodelling**, through the development of scenario-specific LCA datasets, was built upon the baseline datasets developed in the previous phase and reworked to quantify the effects of individual WLC measures within the Italian national context;
- **Literature-based assessments**, adopting indicators and/or reference values derived from the international scientific literature and considered sufficiently reliable and transferable to the Italian context;
- **Qualitative assessments**, based on methodological indications, assumptions, and criteria derived from the scientific literature and technical reference documents.

The combination of these approaches enables the level of analytical investigation to be tailored to the characteristics and complexity of each WLC measure, while ensuring methodological rigour and the efficient use of available data and project resources.

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2.3. Quantitative Assessment and Target Definition

The **third step** (Figure 7) is devoted to the operational implementation of the analysis of those WLC measures for which **case study remodelling** has been identified as the most appropriate analytical approach. The workflow consists of two sequential **filtering phases**: (i) the identification of the building typologies most affected by each WLC measure, followed by (ii) the multi-criteria selection of representative case studies.

The building typologies considered in this step correspond to those defined during the baseline phase, namely Single-Family Houses (SFH), Multi-Family Houses (MFH), Hospitals (HOS), Office Buildings (OFF), Educational Buildings (EDU), and Other Non-Residential Buildings (XTR) (**D7.19**, **D7.20**). This screening is based on the relevance of the LCM associated with the measure, as identified in the WLC measures matrix developed in Step 1, allowing the subsequent analysis to focus on building typologies that are both relevant to the measure under consideration and representative of the case studies analysed within INDICATE LIFE IT. Where appropriate, closely related typologies are aggregated into representative groups to ensure methodological consistency and facilitate the subsequent remodelling activities. These typologies are organised into three categories: (i) **SFH**, (ii) **MFH+HOS**, and (iii) **OFF**. EDU and XTR typologies are excluded for the most of remodelling due to their limited representativeness, as they include a small number of case studies that are highly heterogeneous.

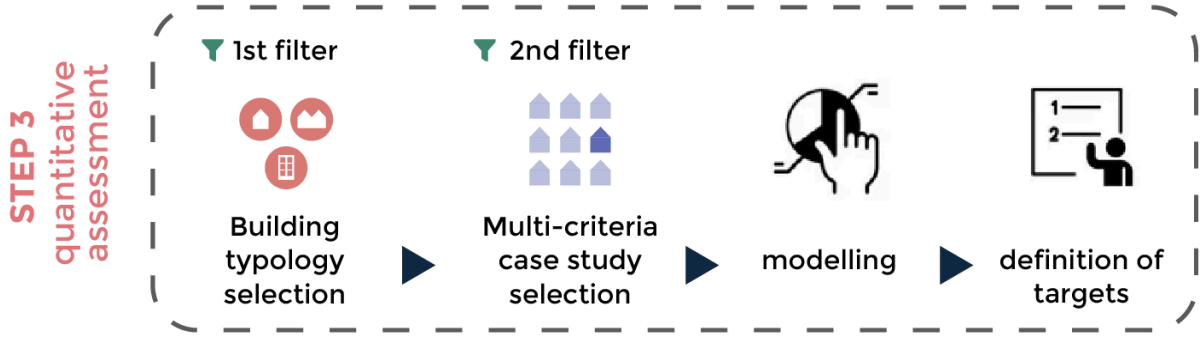


Figure 7: Overall methodological workflow for the quantitative assessment of WLC measures

The second phase is further detailed in Figure 8, which illustrates the sequential filtering workflow used to select representative case studies.

Starting from this typological grouping classification, a preliminary screening is carried out to identify which LCM is expected to produce the most significant effects for each WLC measure. This screening is based on the relevance of the LCM associated with the measure, as identified through the WLC measures matrix developed in Step 1, allowing the subsequent analysis to focus on the selection of **representative case studies** for **each measure**.

For each WLC measure and each identified building typology group, a sequential **filter-based multi-criteria selection process** is then applied to identify both the most representative case studies and those most critical with respect to the measure under examination. As illustrated in Figure 8, the multi-criteria selection process follows a sequential filtering workflow based on the criteria described below:

- **Impact severity:** the relevance of the impact associated with the LCM identified through the WLC measures matrix (Step 1) is assessed, with preference given to case studies exhibiting the highest impact values for that

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module. In this way, remodelling is conducted under a tendentially worst-case condition, allowing the effects of the measure to be discerned more clearly;

- **Construction system representativeness:** the ability of the case study to adequately represent the prevailing construction system is assessed relative to the overall distribution of case studies analysed within the project. This criterion ensures that the selected case studies are not driven by exceptional or atypical constructive characteristics, thereby improving the transferability of the results;
- **Data availability and quality:** case studies are selected according to the completeness, reliability, and consistency of the available inventory data;
- **Remodelling feasibility:** priority is assigned to case studies for which the implementation of the selected WLC measure is technically feasible and methodologically consistent.

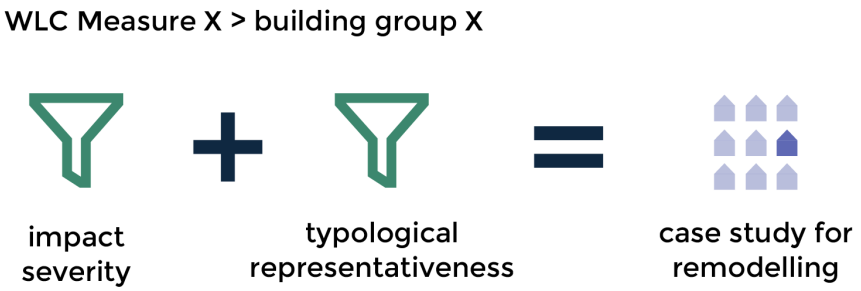


Figure 8: Sequential filtering workflow combining impact severity and typological representativeness to identify representative case studies to be subsequently remodelled

This multi-criteria approach supports a **targeted remodelling strategy** by allowing the selection of the most relevant case studies for each WLC measure, based on building typology, construction characteristics, and environmental impact profile. Remodelling is therefore applied to a selected set of case studies rather than to the entire available sample, prioritising those best suited to assessing the potential benefits in terms of WLC reduction, while preserving sample representativeness.

The outcomes of the case study selection process are detailed in Chapter 5.1 (Description of the modelling).

3. Selection of the pathways

Following the methodological approach described in Section 2.1, the decarbonisation pathways adopted in this deliverable are based on the ASI (Avoid–Shift–Improve) framework. All three pathways were retained and interpreted in relation to the Italian WLC context in order to ensure a comprehensive representation of the different approaches to WLC reduction across the building life cycle.
Within the ASI framework, each pathway comprises one or more strategy packages, which group decarbonisation actions according to their common objective. The **Avoid** pathway includes strategy packages aimed at reducing the demand for new construction and material use through sufficiency and circularity principles. The **Shift** pathway comprises strategy packages that promote the transition to low-carbon construction materials and alternative building solutions. The **Improve** pathway includes strategy packages focused on reducing operational and embodied

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emissions by improving the efficiency of conventional construction practices, materials, and construction processes.
Table 1 summarises the **strategy packages** associated with each of the three **ASI** pathways, as defined in the reference framework, together with their corresponding descriptions. Building on this framework, **Table 2** provides, for each WLC measure, the assessment level adopted in this study.

Table 1: Strategy packages included within the ASI framework. (Source: Rock et al., 2025)

Approach	Strategy packages	Description	WLC strategy
Avoid	Increase circularity and use of existing buildings	Reduce material demand by prioritizing existing building use; improving efficiency of material use; increasing reuse and recycling; and reducing construction and demolition waste (CDW).	2, 3, 8, 10
	Increase use intensity	Reduce per capita space demand in both new construction as well as refurbishment of existing buildings.	1
Shift	Shift to low-carbon bio-based materials	Increase the shift to bio-based construction materials; implement other on-site Carbon Dioxide Removal (CDR) solutions.	4, 11
Improve	Reduce operational emissions	Reduce operational emissions by improving energy demand (e.g. add insulation); energy efficiency (e.g. upgrade systems); and energy emissions (e.g. by switching to low carbon or renewable energy sources)	9
	Increase use of improved materials	Reduce embodied emissions by increasing uptake of improved conventional materials such as low carbon concrete, steel or glass.	5
	Reduce transport and construction emission	Reduce emissions arising from material transport, and during the construction and installation process.	6, 7

To support the subsequent selection of WLC strategies and measures, the ASI framework was further interpreted by mapping the identified strategies across the relevant LCA modules. This additional step, developed within the present deliverable, enables the relationship between the three ASI pathways and the building life cycle stages to be visualised, highlighting where each WLC strategy can contribute to reducing Whole Life Carbon emissions.

Figure 9 presents this interpretation, showing the distribution of the identified WLC strategies across the different LCMs. The figure also highlights the additional WLC measures introduced by the authors to address specific aspects of the Italian context that were not explicitly covered by the original reference framework.

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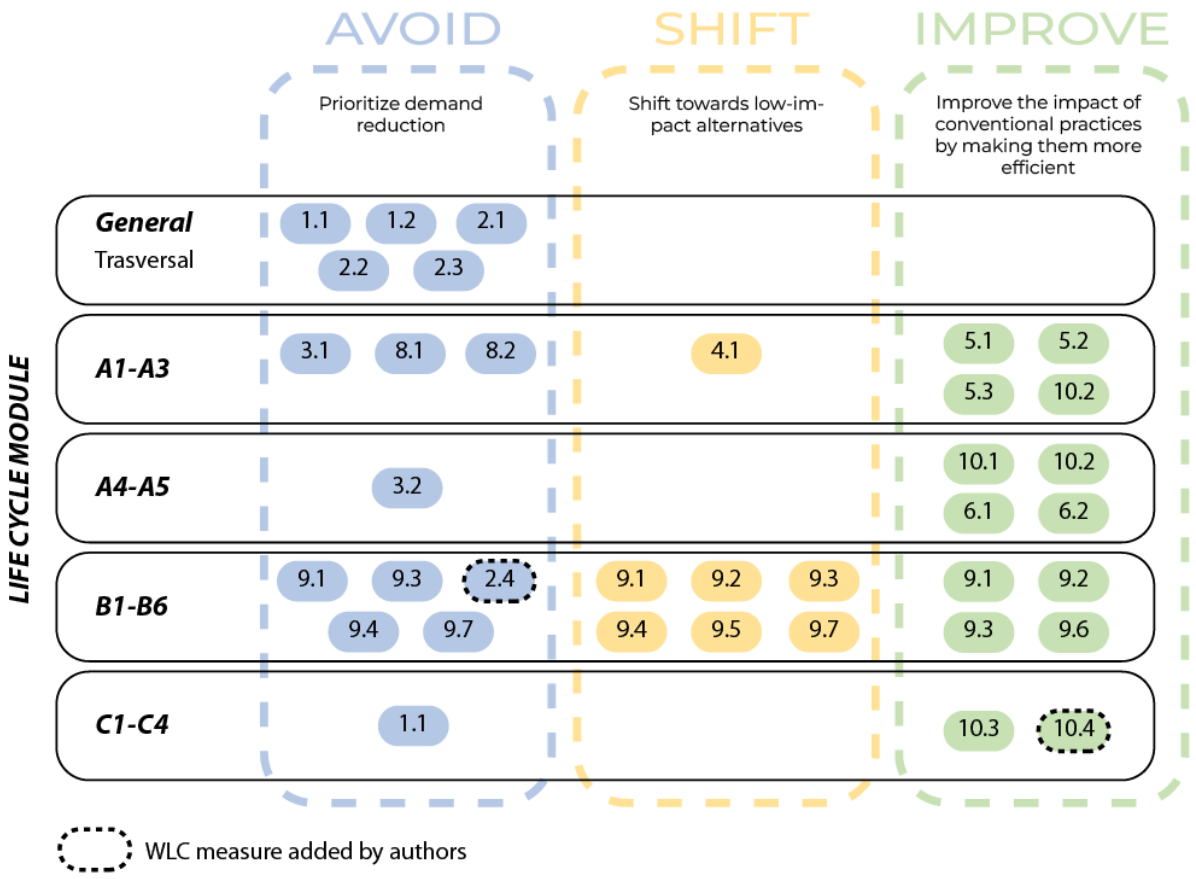


Figure 9: Matrix of WLC measures mapped across LCMs and corresponding ASI pathways

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4.Selection of design strategies in each pathway

This section describes the process through which the design strategies and related **WLC measures** were selected for consideration in the present report. The selection process was developed within the methodological structure defined in chapter 2 and refined through contributions from the Italian Consortium partners.

Drawing on the hierarchical structure adopted in the methodological framework, organised into **ASI pathways**, **strategy packages**, **WLC strategies** and **WLC measures**, the section defines the scope of the strategies analysed and their corresponding level of assessment.

With reference to the **strategy packages** listed in **Table 1**, all packages were considered, with the exception of **"Increase use intensity"**. This exclusion is justified by the fact that the strategies associated with this package would require a substantial redefinition of space use, internal layout and building occupancy profiles, aspects that are not sufficiently documented in the available case studies. In particular, the absence of reliable data on the actual number of occupants and real patterns of space use does not allow a robust and internally comparable assessment to be developed within the national dataset.

As illustrated in Table 1 and according to the hierarchical structure represented in Figure 4, each strategy package may include one or more WLC strategies, which are in turn articulated into specific WLC measures. The selection operates mainly at these two lower levels, since WLC strategies and, above all, WLC measures represent the levels most directly translatable into modelling actions.

For each measure, the assessment approach was selected according to a consistent set of criteria, including its relevance to decarbonisation objectives, data availability within the Italian consortium, remodelling feasibility and consistency with the scope and characteristics of the analysed case studies. This section therefore consolidates the justifications for excluding the WLC strategies not considered in the present analysis. The justifications for excluding individual WLC measures belonging to strategies that were otherwise assessed are instead reported in the subsequent summary table.

The resulting selection therefore reflects not only the relevance of the strategies to WLC reduction, but also their methodological assessability within the available Italian case-study dataset. The WLC strategies excluded from the scope of analysis are the following:

WLC strategy 1 – Reduce per capita space demand.
This strategy was not considered in the present study because its assessment would require a design-level reworking of the real case studies, affecting internal layout, space-use intensity and occupancy profiles. The modelling of measures such as space-use optimisation or functional densification of buildings would require detailed information on the actual number of occupants, the ways in which spaces are used, and the design feasibility of redefining internal spaces. Such information was not systematically available for the case studies analysed by the Italian consortium. As a result, the application of this strategy would have required design assumptions that were not sufficiently verifiable and would have been difficult to compare across buildings.

WLC strategy 4 – Increase the use of bio-based materials (material shift).
This strategy was not included in the analysis because the substitution of conventional materials with bio-based materials cannot be treated as a simple direct replacement within the available models. In many cases, the use of bio-based

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materials would require a revision of the dimensional, performance-related and construction characteristics of the technical assemblies, with possible effects on hygrothermal behaviour, energy performance, durability, fire resistance and compatibility with the original construction system. Since the analysis is based on real case studies that had already been designed and modelled in the baseline, a coherent remodelling of this strategy would have required a partial redesign of the technical elements involved, introducing a level of assumptions that would not be compatible with the objective of maintaining traceability and comparability with the initial datasets.

WLC strategy 7 – Reduce emissions from the construction site.
This strategy was not assessed because, within the baseline, module **A5** was modelled through assumptions derived mainly from the impacts of products and materials accounted for in modules **A1-A3**. This approach does not make it possible to isolate in sufficient detail the specific contributions of the construction site, such as machinery use, temporary energy consumption, internal logistics, site equipment or the optimisation of operational activities. Consequently, it is not possible to robustly assess measures such as the use of alternative fuels in construction machinery or the optimisation of machinery use, since the available dataset does not contain specific and disaggregated information on construction-site activities.

Based on this selection process, the strategies and measures considered applicable are subsequently classified according to the assessment approach adopted. Figure 10 summarises the WLC measures actually considered within the ASI–life cycle modules matrix, while Table 2 reports the overall framework of strategies, associated measures and their corresponding level of assessment: quantitative approach, qualitative approach or not assessed.

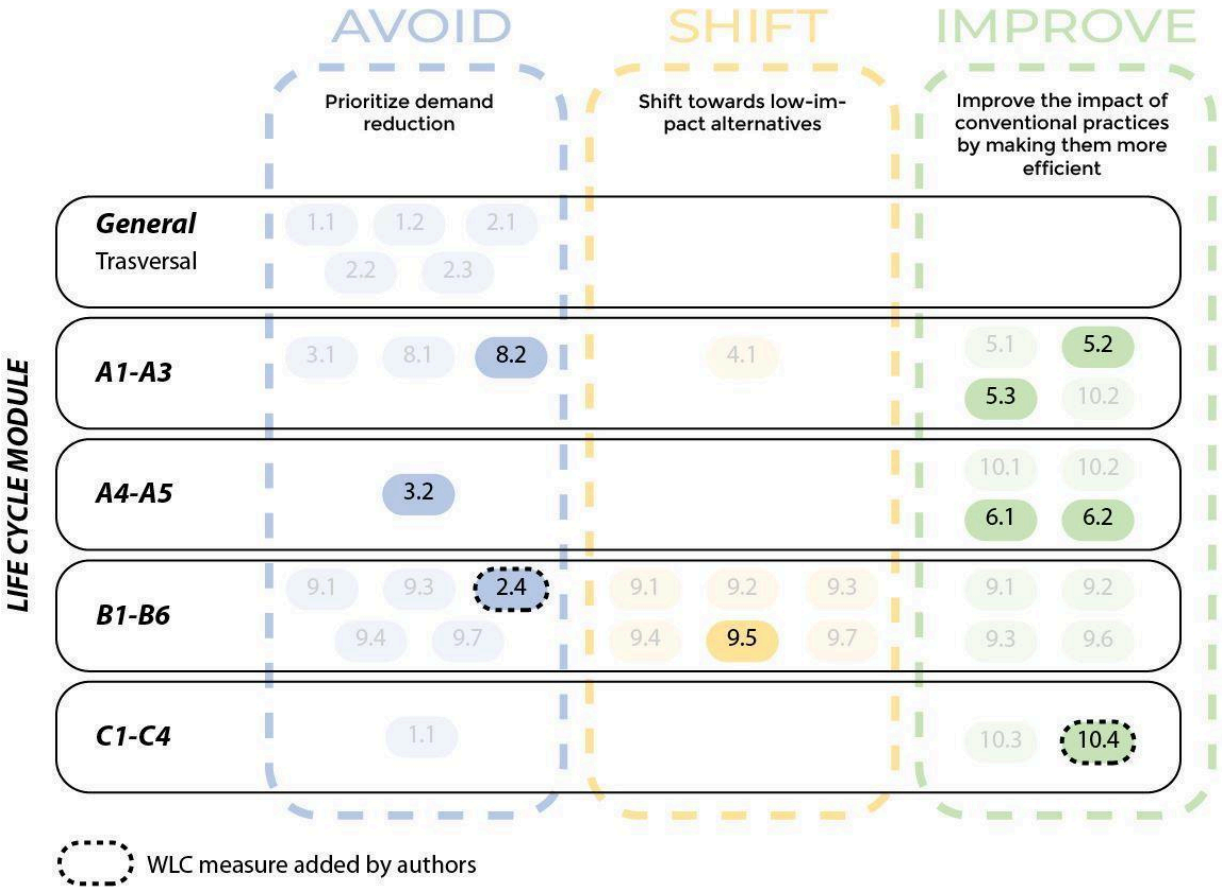


Figure 10: Matrix with WLC measure assessed

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Table 2: Overview of ASI pathways, WLC strategies and related measures, with indication of the assessment level adopted for each measure

WLC strategy	ASI pathways	WLC measure		Quantitative approach	Qualitative approach	Not assessed
1. Reduce per capita space demand	Avoid	1.1	Optimise the use of space in buildings			X
	Avoid	1.2	Re-designing buildings for denser use			X
2. Prioritise better use, renovation and repair over demolition and new construction	Avoid	2.1	Extend building lifetime through renovation			X
	Avoid	2.2	Vacancy reduction			X
	Avoid	2.3	Design for flexibility and adaptability			X
	Avoid	**2.4***	Design for durability and maintainability of building components	X		
3. Improve material efficiency	Avoid	3.1	Material use optimisation in structural design			X
	Avoid	3.2	Offsite construction		X	
4. Increase the use of bio-based materials	Shift	4.1	Increase the use of bio-based materials			X
5. Reduce emissions from traditionally high-impact construction materials	Improve	5.1	Substitution with low-carbon input materials in production			X**
	Improve	5.2	Renewable energy sources in production	X		
	Improve	5.3	Carbon capture, utilisation and storage in production	X		
6. Reduce emissions from the transport of materials and construction products	Improve	6.1	Use of locally sources materials	X		
	Improve	6.2	Use of alternative fuels in transportation	X		
7. Reduce emissions from the	Improve	7.1	Use of alternative fuels in construction machinery			X

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construction site	Improve	7.2	Machine use optimisation			X
8. Increase circular material use	Avoid	8.1	Re-use existing building components and materials			X
	Avoid	8.2	Use of materials with high recycled content	X		
	Avoid	8.3	Design for disassembly			X
9. Reduce operational carbon emissions	Avoid - Shift - Improve	9.1	Reduce energy for space heating and cooling			X
	Shift - Improve	9.2	Reduce energy for ventilation			X
	Avoid - Shift -/ Improve	9.3	Reduce energy for water heating			X
	Avoid - Shift	9.4	Reduce energy for lighting			X
	Shift	9.5	Increase renewable energy	X		
	Improve	9.6	Improve facility management			X
	Avoid - Shift	9.7	Include tenants			X
10. Reduce construction and demolition waste	Improve	10.1	On-site waste material sorting and separation			X
	Improve	10.2	Reduce construction packaging			X
	Improve	10.3	End of Life audits and waste audits			X
	Improve	**10.4***	Improved end-of-life scenarios		X	
11. Use of carbon dioxide removal (CDR) solutions	Removals	11.1	Green roofs and/or green façades	X		
	Removals	11.2	Increased use of biochar			X
	Removals	11.3	Direct air capture (DAC)			X

*Additional WLC measures introduced by the authors to complement the measures identified in the reference reports.

**The measure is considered in the WLC measure 5.3 only for concrete material.

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5. Description of the modelling

This chapter describes the **methodological implementation** of the WLC measures assessed through a **quantitative approach**, as identified in Section 2.3. The objective is to provide a transparent account of how each measure was modelled, specifying the assumptions adopted, the modifications introduced into the reference datasets, and the criteria used to implement the remodelling process.

For each measure assessed quantitatively, the main methodological assumptions, calculation procedures, and remodelling choices applied to the reference dataset are described. Where relevant, the buildings subject to modification, the building elements concerned, and the products or materials replaced or modified are specified. The quantitative remodelling activities were coordinated by UNIBG, which defined the allocation of the selected WLC measures and representative case studies among the participating research units. The remodelling was then carried out by UNIBG, POLITO and POLIMI according to the common methodological approach defined in previous chapters. Across the WLC measures assessed quantitatively, UNIBG contributed to the remodelling of eight measures, POLITO to four measures and POLIMI to two measures, including measures jointly assessed by more than one research unit. The specific allocation of measures and case studies to each research unit is reported in the following subsections.

The corresponding quantitative results are presented in Chapter 6.

5.1. Selection process of representative case studies

For the WLC measures assessed through a quantitative approach, representative case studies were selected by applying the sequential filtering procedure introduced in the methodological framework (Chapter 2.1). This procedure provides the common methodological basis for identifying the case studies to be used in the quantitative remodelling activities.

This process aims to identify, for each WLC measure and for each relevant building typology group, one or more case studies suitable for remodelling. The selection does not rely on a random extraction of cases, but on a multi-criteria prioritisation process designed to combine typological representativeness, impact relevance, data robustness, and remodelling feasibility.

Starting from the typological groups identified in the preliminary phase of the procedure, namely SFH, MFH+HOS, and OFF, the selection process first considers two criteria expressed through numerical scores:

- **constructive typology**, adopted as a proxy for typological representativeness;
- **impact intensity**, used to identify the case studies with the highest relevance in relation to the LCM targeted by each WLC measure.

These two criteria are used to build an initial prioritisation framework, in which each case study is assigned a score ranging from 0 to 1 for each criterion. The sum of the two scores provides a preliminary ranking of the case studies and supports the identification of those that are both representative of the building stock and relevant in terms of potential WLC reduction.

Specifically, **constructive typology** is quantified according to the distribution of constructive systems observed within the analysed case studies, as reported in the **D7.20**. A score of 1.00 is assigned to case studies characterised by reinforced concrete (RC) structures, which represent the most recurrent construction typology among the analysed case studies. A score of 0.75 is assigned to mixed reinforced concrete and

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steel frame systems (RC+SF), 0.50 to masonry structures (MA), and 0.25 to mixed reinforced concrete and masonry systems (RC+MA). In this way, case studies belonging to more representative constructive typologies are prioritised, while less recurrent systems are still retained within the selection framework but assigned a lower priority.

Impact intensity is instead assessed with reference to the LCM associated with each WLC measure. For each measure, the relevant LCM is identified according to the WLC measures matrix developed in Step 1. The impacts associated with that module are then compared across the available case studies belonging to the same typological group. A normalised score ranging from 0 to 1 is assigned proportionally to the relative impact ranking of each case study, with higher values attributed to cases showing greater impact intensity in the module under consideration. This allows the remodelling activity to focus on case studies where the selected WLC measure is expected to produce more significant and measurable effects.

The combination of these two quantified criteria provides an initial **prioritisation framework** to support the selection of case studies.

Case studies with higher combined scores are considered more suitable for remodelling, as they simultaneously reflect relevant constructive characteristics and a high impact contribution in the LCM targeted by the WLC measure. This step therefore supports a more transparent and reproducible selection process.

The final selection of case studies is presented in Figures 12, 13 and 14, according to the LCMs addressed by the WLC measures considered. Figure 12 reports the multi-criteria ranking for the measures affecting modules A1–A3; Figure 13 presents the ranking for the measures associated with module B4; and Figure 14 reports the ranking for the measure related to module A4.

However, the final selection is not based exclusively on the numerical score. The preliminary ranking is further refined by applying two additional qualitative criteria, namely data availability and quality, and remodelling feasibility, both of which are described in Chapter 2. Overall, this **filtering procedure** enables the definition of a structured framework of **representative** and critical **case studies** for the **quantitative assessment** of WLC measures. By combining normalised scores for constructive typology and impact intensity with qualitative checks on data quality and modelling feasibility, the selection process ensures that the subsequent remodelling activities are focused on case studies with high analytical relevance, adequate representativeness, and sufficient methodological robustness.

A1-A3			
SFH	IMPACT	STR. TYPE	RESULT
SFH_10	1	0.5	1.5
SFH_02	0.9	0.75	1.65
SFH_09	0.9	1	1.9
SFH_08	0.7	1	1.7
SFH_11	0.6	0.25	0.85
SFH_01	0.5	0	0.5

A1-A3			
MFH	IMPACT	STR. TYPE	RESULT
MFH_24	1	1	2
MFH_02	1	1	2
HOS_03	1		1
MFH_01	1	1	2
MFH_19	0.8	0.75	1.55
MFH_27	0.8	1	1.8
MFH_22	0.8	1	1.8
HOS_06	0.7	0.25	0.95
MFH_14	0.7	1	1.7
HOS_05	0.5	0.75	1.25

A1-A3			
OFF	IMPACT	STR. TYPE	RESULT
OFF_11	1	1	2
OFF_10	0.9	0.75	1.65
OFF_01	0.9	0.5	1.4
OFF_09	0.9	0.75	1.65
OFF_13	0.7	1	1.7
OFF_08	0.6	1	1.6
OFF_07	0.5	1	1.5

Figure 12: Multi-criteria ranking of new construction case studies by typology group for WLC measures 5.2 and 8.2. MFH_01 is considered for WLC measure 5.3.

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B4			
ALL	IMPACT	TYPOLOGY	RESULT
MFH_18	1	1	2
SFH_08	1	0.5	1.5
OFF_09	1	0.75	1.75
MFH_01	0.7	1	1.7
SFH_01	0.7	0.5	1.2
OFF_13	0.6	0.75	1.35
MFH_22	0.6	1	1.6
OFF_10	0.5	0.75	1.25
MFH_02	0.4	1	1.4
OFF_11	0.4	0.75	1.15
OFF_08	0.3	0.75	1.05

Figure 13: Multi-criteria ranking of new construction case studies for all typologies for WLC measure 2.4.a, 2.4.b

A4			
ALL	IMPACT	TYPOLOGY	RESULT
SFH_10	1	1	2
SFH_02	0.7	0.5	1.2
MFH_24	0.7	1	1.7
MFH_18	0.7	1	1.7
HOS_06	0.6	0.25	0.85
MFH_27	0.6	1	1.6
MFH_22	0.6	1	1.6
HOS_05	0.5	0.25	0.75
HOS_03	0.4	0.25	0.65

Figure 14: Multi-criteria ranking of new construction case studies by residential case studies for WLC measures 6.2

The procedure described above represents the general methodological reference for selecting the case studies to be remodelled. However, not all WLC measures assessed through the quantitative approach follow the full sequence of the case study selection procedure. For some measures, an adapted procedure is applied: the multi-criteria selection framework is used across the entire set of available case studies, without first grouping them by building typology.

This approach is adopted when a typology-based distinction does not provide substantial methodological added value, or when the quantitative assessment is mainly exploratory and aims to evaluate how individual case studies respond to the selected measure.

Table 3 summarises the outcome of the selection procedure for each WLC measure assessed through the quantitative approach. For each measure, it reports the LCM or modules concerned, the case studies selected for each building typology group and, where relevant, the specific way in which remodelling is applied. The table therefore clarifies the set of case studies used as the basis for subsequent remodelling activities and distinguishes between measures applied to selected representative cases, those addressed through a single technological element, and those measures extended to the full set of new construction case studies.

The resulting set of **representative case studies** provided the common basis for the subsequent quantitative **remodelling activities** carried out by the participating research units.

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Table 3: Case studies selected for quantitative remodelling by WLC measure, LCM and typology group

WLC measure	LCM	Case study		
		SFH	MFH+HOS	OFF
2.4	B4	(MFH_18)*		
5.2	A1-A3	SFH_09, SFH_10	MFH_01, MFH_14	OFF_11, OFF_13
5.3	A1-A3	(MFH_01)*		
6.1	A4-A5	(SFH_10)*		
6.2	A4-A5	(SFH_10)*		
8.2	A1-A3	SFH_09, SFH_10	MFH_01, MFH_14	OFF_11, OFF_13
9.5	B1-B6	Modelling performed for all New Construction case studies.		
11.1	B1-B6	Modelling performed on the individual case study with characteristics consistent with the remodelling procedure: MFH_11.		

*Measure assessed on a single representative case study or typology because the effect is considered mainly related to the specific design or modelling assumption rather than to typological variation. The result is used as a reference value for all the building categories considered in the report.

The quantitative remodelling activities associated with the selected case studies were distributed among the participating research units. UNIBG contributed to WLC measures 2.4, 5.2, 5.3, 6.1, 6.2, 8.2 and 9.5, and jointly with POLITO to WLC measure 11.1; POLITO also contributed to WLC measures 5.2, 5.3 and 8.2; and POLIMI contributed to WLC measures 5.2 and 8.2.

5.2. WLC strategies

This section presents the WLC strategies considered in the assessment. For each strategy, the corresponding WLC measures are reported and briefly described, in order to clarify the scope of the analysis and the specific decarbonisation actions addressed. The assessment of each measure follows the methodological approach and case-study selection process described in the previous sections. For the specific WLC measures not assessed, motivation for their exclusion is provided, with reference to methodological constraints, data availability, modelling feasibility, or limited relevance within the context of the analysed case studies. An overview of the WLC strategies is provided in Table 4, together with a guide to the structure of the following subsections.

Table 4: Document sections of strategies described

WLC strategies	Description	Document section
Strategy 2	Prioritise better use, renovation and repair over demolition and new construction	5.2.1

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Strategy 3	Improve material efficiency	5.2.2
Strategy 5	Reduce emissions from traditionally high-impact construction material	5.2.3
Strategy 6	Reduce emissions from transport of materials and construction products	5.2.4
Strategy 8	Increase circular material use	5.2.5
Strategy 9	Reduce operational emissions	5.2.6
Strategy 10	Reduce construction and demolition waste	5.2.7
Strategy 11	Use of carbon dioxide removal (CDR) solutions	5.2.8

5.2.1. Strategy 2 description: Prioritise better use, renovation and repair over demolition and new construction

WLC Strategy 2 addresses the reduction of whole-life carbon impacts by prioritising the better use of existing buildings, renovation and repair over demolition and new construction. Within the overall WLC framework, this strategy includes the following measures:

- 2.1 Extend building lifetime through renovation
- 2.2 Vacancy reduction
- 2.3 Design for flexibility and adaptability
- **2.4 Design for durability and maintainability of building components** (added by Authors)

Based on the national WLC datasets developed from the 50 case studies presented in **D7.20**, Measures 2.1–2.3 were not subject to further assessment within the present deliverable for the following reasons:

- **Measure 2.1 – Extend building lifetime through renovation.** This measure is already implicitly addressed within the baseline assessment. Renovation interventions were modelled using an expanded life cycle approach, considering all LCMs from **A1** to **C4**, rather than limiting the assessment to module **B5** alone. Consequently, the effects associated with extending building lifetime through renovation are already reflected in the results presented in **D7.20**;
- **Measure 2.2 – Vacancy reduction.** Although reducing building vacancy through the adaptive reuse of existing buildings is widely recognised as an effective strategy for reducing WLC impacts and promoting the circular use of the existing building stock, the review carried out for the Italian context highlighted the absence of a sufficiently structured and representative knowledge base to support a robust quantitative assessment. The available evidence mainly consists of individual case studies and exemplary projects, while systematic datasets describing the characteristics, distribution, and environmental performance of vacant buildings suitable for adaptive reuse are currently lacking (Mourão, 2026). Consequently, the available information is

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heterogeneous and not fully compatible with the methodological approach adopted in this project, limiting the feasibility of a consistent quantitative assessment;

- **Measure 2.3 – Design for flexibility and adaptability.** This measure was not assessed due to the absence of data documenting the application of flexibility and adaptability principles within the analysed case studies. Consequently, it was not possible to quantitatively characterise the influence of this strategy in the Italian context.

Within WLC Strategy 2, particular attention was instead devoted to **Measure 2.4 – Design for Durability and Maintainability of Building Components**, introduced in the present deliverable as an extension of the reference framework.

Extending the service life of building components through durability-oriented design and planned maintenance is recognised as an effective strategy for reducing WLC impacts (Baratta et al., 2023; Condotta & Zatta, 2020), by reducing the need for premature replacement, promoting a more efficient use of material resources, and improving the long-term environmental performance of buildings. Measure 2.4 was therefore introduced in the analysis and selected for subsequent quantitative modelling.

Measure 2.4: Design for durability and maintainability of building components

The following sections describe the methodological approach adopted for the assessment of Measure 2.4.

Measure 2.4 aims to assess how improving the management of replacement cycles modelled for **module B4** influences the overall WLC balance. In this regard, the hotspot analysis conducted on the complete case study dataset identified **module B4 (Replacement)** as a relevant contributor to greenhouse gas emissions.

In this context, the determining factor is not exclusively the carbon intensity of the material itself, but rather its replacement frequency, which depends on the expected **Service Life (SL)** of the building element considered (e.g. external wall finishes).

The measure therefore evaluates the potential benefits of adopting planned maintenance strategies for technical components and finishes. The assessment considers the balance between the embodied impacts generated by periodic maintenance interventions and the impacts avoided by postponing or reducing complete replacement cycles. From an operational perspective, the analysis aims to quantify the extent to which ordinary maintenance, accounted for through its embodied carbon (EC) contribution in **module B2**, can reduce the number of replacement cycles within the **Reference Study Period (RSP)** and consequently decrease the impacts attributed to **module B4**. The baseline scenario is defined according to the Level(s) framework for residential buildings. For office buildings, dedicated service life values defined within **D7.20** were adopted.

Considering the large number of variables affecting the replacement scenarios modelled in module B4, a precautionary approach was adopted. Consequently, the detailed analysis was limited to MFH (Multy Family House), which represents the most recurrent building typology within the analysed case study dataset.

The assessment focuses on the building element categories included in **Tier 2.1**, for which the **Level(s)** framework assigns the following service lives:

- **30 years** for floor finishes;
- **20 years** for internal wall finishes and suspended ceilings.

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Assuming a RSP of 50 years, these service lives correspond to one replacement cycle for floor finishes and two replacement cycles for internal wall finishes and suspended ceilings.

The proposed assessment is structured into two complementary approaches, each addressing a different methodological objective. **Approach A** aims to reduce the impacts associated with replacement (module B4) **by optimising replacement cycles through component disaggregation**. Conversely, **Approach B** evaluates the balance between the additional embodied impacts generated **by planned maintenance** (module B2) **and the reduction of impacts associated with replacement** (module B4). Table 5 summarises the methodological characteristics of both approaches. In particular, Columns 2 and 3 present Approaches A and B, respectively, together with the corresponding greenhouse gas accounting methods and calculation procedures adopted for the assessment.

Table 5: Methodological approaches adopted for the assessment of WLC Measure 2.4

WLC measure 2.4		
Assessment aspect	**A (2.4a) Component/Sub-component disaggregation**	**B (2.4b) Planned maintenance as an alternative to full replacement**
Accounting methods	Optimisation of the replacement cycle identified in the baseline for the specific case study.	Increase in the EC value in module B2 for additional routine maintenance activities.
Methodological framework	For some component categories, the SL value provided by Level(s) refers to an aggregated building element. However, several sub-components may have intrinsically different life cycles. In these cases, assuming the full replacement of the entire element can lead to an overestimation of B4 impacts, as it does not adequately reflect actual maintenance and replacement practices.	For finishing materials whose SL is shorter than the RSP, a planned maintenance scenario is modelled to postpone or reduce full replacement. Unlike Approach A, Approach B introduces an additional maintenance intervention, resulting in an increase in EC in module B2. The default value for module B2, expressed as a percentage of the A1–A3 impacts, is replaced by a case-specific assessment of the maintenance scenario, explicitly modelling the quantities of materials involved and the frequency of maintenance interventions.
Application	Remodelling of plasterboard partitions through the reuse of the supporting substructure over the RSP.	Remodelling of the paint finishing layer, considering scheduled maintenance of the finishing layer as an alternative to full replacement over the RSP. The additional EC associated with maintenance interventions is explicitly accounted for.

Considering the assumptions summarised in Table 5, Approach A can be interpreted as an optimisation of the baseline assumptions, as it refines a potentially conservative

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replacement hypothesis through component disaggregation. Conversely, Approach B represents a maintenance-oriented strategy, whose effectiveness depends on the balance between the impacts avoided by postponing or reducing full replacement and the additional EC associated with the maintenance activities introduced in the assessment.

Within Approach B, scheduled maintenance is considered as an alternative to the complete replacement of the paint finishing layer. The EC associated with maintenance activities is accounted for in module B2, while the avoided or postponed replacement of the corresponding component is reflected through a reduction of impacts in module B4.

The following sections describe the maintenance scenarios developed for the materials whose service life is shorter than the RSP:

- **Indoor paint.** The baseline assumes the complete replacement of the paint layer every 20 years, corresponding to two replacement cycles over the RSP. This assumption reflects a conventional replacement-based approach and does not consider maintenance interventions capable of extending the service life of the finish while avoiding complete renewal. The alternative scenario introduces an intermediate maintenance intervention, consisting of localised touch-ups or the application of a single finishing coat on surfaces that remain in good condition. The alternative scenario assumes an intermediate maintenance intervention consisting of localised touch-ups or the application of a single finishing coat to surfaces that remain in good condition. The modelling assumption is based on the technical specifications of a commercial paint product considered representative of the Italian market. According to the manufacturer's technical data sheet, the product is characterised by a practical coverage of 9–12 m^2/L per coat, a maximum dilution of 10%, and an application cycle consisting of two finishing coats on substrates with well-adhered existing water-based paint (Boero Bartolomeo S.p.A., 2021). These characteristics were adopted as the reference assumptions for modelling the maintenance scenario;

- **Gypsum plasterboard partition walls.** Compared with the baseline scenario, in which the complete replacement of plasterboard partition walls every 30 years is assumed in accordance with the Level(s) service life assumptions, including both the plasterboard boards and the galvanised steel substructure (studs and tracks), the proposed scenario considers the reuse of the supporting metal substructure, as it is not expected to undergo significant degradation under normal indoor service conditions throughout the RSP. Accordingly, in the modelling of module B4, replacement is limited to the plasterboard boards and the associated finishing materials, while the metal substructure is considered to be reused and is therefore excluded from the replaced quantities. This methodological assumption, introduced in the present deliverable, is justified by the technical characteristics of dry construction systems and the expected durability of galvanised steel profiles in indoor environments. Overall, this measure evaluates the potential benefits of adopting a circular approach based on design for disassembly and component reuse, limiting replacement to those elements that are actually subject to deterioration or functional renewal.

5.2.2. Strategy 3 description: Improve material efficiency

WLC Strategy 3 aims to reduce WLC through a more efficient use of construction materials. To this end, it comprises the following two measures:

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- 3.1 Material use optimisation in structural design;
- **3.2 Off-site construction.**

Both measures primarily target the reduction of EC associated with the production of construction materials and building components, with direct implications for modules A1–A3.

Measure 3.1 aims to reduce material demand through structural design optimisation by limiting unnecessary over-specification and improving resource efficiency. However, this measure was not included in the assessment carried out within the present deliverable, as its application would require detailed structural design information that is not consistently available across the analysed case studies, including design loads, structural schemes, reinforcement ratios, member sizing, and alternative optimisation scenarios. Furthermore, the potential material savings depend strongly on project-specific design choices, regulatory and performance requirements, and the level of optimisation already embedded in the original design. In the absence of such information, any quantitative assessment would have introduced a level of uncertainty that is not consistent with the methodological approach adopted in the present study.

Measure 3.2, on the other hand, concerns the adoption of **off-site construction systems**, based on the industrialised production of prefabricated building components subsequently assembled on site. This approach has the potential to contribute to reducing material waste (**modules A5 and C1–C4**), improving production control, and increasing construction efficiency (**module A5**).

As the INDICATE LIFE IT case study dataset does not include buildings constructed using off-site systems, the measure could not be assessed through quantitative modelling. Instead, its potential contribution to WLC reduction was investigated through a **qualitative assessment** based on a critical review of the available scientific literature. This review provides an evidence-based overview of the environmental benefits, methodological limitations, and applicability of the main off-site construction technologies, thereby supporting the evaluation of the measure within the methodological framework adopted in this deliverable.

The literature identifies two main technological solutions:

- **Precast concrete systems**, consisting of structural elements such as beams, columns, and slabs manufactured in a factory and subsequently assembled on site;
- **Timber modular systems**, consisting of prefabricated panels and volumetric modules assembled on site using dry construction techniques.

Considering the limited representativeness of CLT-based construction within the INDICATE LIFE IT case study dataset, the literature review focused on precast reinforced concrete systems, which are more representative of the analysed building stock.

For **precast reinforced concrete building elements**, the literature reports **GHG emission reductions ranging approximately from 8% to 15%** compared with conventional cast-in-place construction (Karlsson et al., 2021; Jayawardana et al., 2023). These benefits derive from the combined contribution of the material supply, transportation, and both off-site and on-site construction stages. Among these, the most significant reduction is associated with the **construction stage (module A5)**, owing to the higher efficiency, standardisation, and process control achieved under factory production conditions compared with conventional on-site construction.

Focusing specifically on **module A5**, Jayawardana et al. (2023), comparing a fully cast-in-place concrete structure with a partially prefabricated solution, reported a

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37.20% reduction in GHG emissions during the construction stage alone. This reduction results from the combined accounting of on-site and off-site construction activities and is mainly attributable to the elimination of formwork installation, concrete casting, and curing operations on site, together with the higher quality, predictability, and efficiency of factory production processes.

A common methodological limitation should nevertheless be acknowledged. In the available studies, emissions associated with the manufacturing plant are generally estimated by allocating the total annual energy consumption of the production facility to its total annual production. Consequently, the impacts attributed to the construction stage primarily reflect the overall efficiency of the manufacturing plant rather than the characteristics of the specific project under assessment.

To support the qualitative assessment of Measure 3.2, the evidence collected through the literature review was synthesised to identify the main factors influencing the environmental performance of off-site construction systems. Table 6 summarises the potential implications of these factors for WLC, highlighting both the opportunities and the limitations identified in the reviewed literature.

Table 6: Main implications of off-site construction systems for WLC, as identified through the literature review

Aspect	Potential influence on WLC	Description	Reference
Transportation of prefabricated elements	Potential increase	The number of transport operations generally remains comparable to cast-in-place construction. Dedicated heavy-duty vehicles and permits for oversized loads are required, making the distance between the manufacturing plant and the construction site the determining factor for transport-related emissions.	Sandanayake et al., 2019
Construction stage	Potential reduction	Reduced and better-controlled construction activities. Elimination or reduction of formwork installation, concrete casting, and curing operations on site, together with higher efficiency, standardisation, and process control under factory production conditions.	Sandanayake et al., 2019; Jayawardana et al., 2023
	Potential increase	Possible increase in indirect emissions of CO, NOx, and particulate matter associated with the greater use of equipment during transportation and installation.	Sandanayake et al., 2019
Construction waste	Potential reduction	Construction waste generated over the building life cycle can be reduced by up to 60% through the use of prefabricated systems, facilitating material recovery at the end of life.	Pons, 201

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Structural applicability	Potential limitation	Only approximately 14% of current reinforced concrete applications are considered suitable for conversion to prefabricated solutions. Certain load-bearing elements, such as foundations, remain difficult to prefabricate.	Allwood et al., 2019
Structural applicability in seismic areas	Conditional limitation	Seismic performance equivalent to cast-in-place reinforced concrete must be demonstrated through appropriately designed beam-to-column connections. Experimental evidence shows that equivalent structural performance can be achieved through suitable connection design.	Jo et al., 2023

5.2.3. Strategy 5 description: Reduce emissions from traditionally high-impact construction material

WLC Strategy 5 aims to reduce WLC by addressing the emissions along the manufacturing process of main building materials. To this end, it comprises the following three measures:

- 5.1 Substitution with low-carbon input materials in production;
- **5.2 Renewable energy source in production;**
- **5.3 Carbon capture, utilisation and storage in production.**

This strategy primarily targets modules A1-A3, where the extraction, processing, and manufacturing of construction materials and products are accounted for. It focuses on materials that traditionally make a significant contribution to EC. Measure 5.1 concerns the replacement of conventional input materials with lower-carbon alternatives, for example through recycled, secondary, bio-based, or otherwise less carbon-intensive inputs. Measure 5.2 addresses the reduction of production-related emissions through the use of renewable energy sources in manufacturing processes. Measure 5.3 refers to the potential application of Carbon Capture, Utilisation and Storage technologies in industrial production processes, particularly for hard-to-abate materials.

In this report, Measure 5.1 is not further assessed as an autonomous measure for this reason:

- The substitution of conventional input materials with low-carbon alternatives requires product- and process-specific information on material composition, supply chains, substitution rates, and technical performance. It is important to note that the material database developed by the Italian Consortium in **D7.20** already incorporates, where available, data representative of national production processes. Consequently, some current low-carbon production inputs are already reflected in the GWP values, while further alternatives identified in the scientific literature do not yet have a sufficiently established counterpart in industrial practice. In addition, some aspects related to secondary or low-carbon inputs are already partially addressed in other

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measures dealing with recycled content and circular material use. For these reasons, Measure 5.1 is not modelled separately in order to avoid overlaps with other WLC measures and to preserve methodological consistency.

Measure 5.2: Renewable energy sources in production

The assessment of the emission reduction potential associated with the progressive decarbonisation of production processes through the adoption of renewable energy sources was developed through two complementary assessment scenarios, representing a **short-term horizon (2030)** and a **long-term horizon (2050)**, respectively.

The first scenario was developed based on the projected evolution of the Italian medium-voltage electricity mix, which is used to model the production processes of construction materials and is described in WLC measure 9.5. In particular, the scenario incorporates the targets defined in the Italian National Integrated Energy and Climate Plan (PNIEC 2024), according to which electricity generation from renewable energy sources is expected to increase from 118.7 TWh in 2021 to 227.8 TWh by 2030, resulting in an increase in the share of renewable electricity in gross domestic electricity consumption from 36.0% to 63.4% (RSE, GSE, Terna, PNIEC 2024).

Based on these assumptions, the Italian electricity mix was remodelled and its influence was evaluated for construction materials representative of the national production system and characterised by energy-intensive manufacturing processes, namely concrete, bricks, natural stone, glass, and ceramic finishes.

The application of this scenario resulted in only limited reductions in GWP, mainly because the electricity mix projected for 2030, although characterised by a significant increase in the share of renewable energy, still represents an intermediate stage in the decarbonisation pathway and therefore introduces relatively limited changes compared with the current production configuration. Furthermore, for many construction materials, energy-related emissions account for only part of the overall GWP, which continues to be strongly influenced by other factors associated with raw materials and manufacturing processes.

To represent the emission reduction potential achievable under a longer-term decarbonisation pathway, a second level of analysis was subsequently developed based on the most recent scientific literature. Two closely related references were selected for this purpose.

The study carried out within the framework of the **European Commission DG GROW project** (Alaux et al., 2024) provides the methodological basis for defining decarbonisation scenarios for construction materials at the European scale. **Based on this methodological framework**, Pristerà et al. (2026) compared the conventional production processes of **aluminium, bricks, concrete, glass, and steel** with alternative production scenarios based entirely on the use of renewable energy sources (**RES scenario**), quantifying the corresponding environmental impact reduction factors.

Within the present study, the reduction factors proposed by Pristerà et al. (2026) were analysed and interpreted for application within the INDICATE LIFE methodological framework. This process involved not only the selection of the GWP fossil reduction factors applicable to the construction materials considered in the project, but also the identification of the corresponding decarbonisation strategies and the methodological assumptions underlying each scenario.

The outcome of this methodological elaboration is summarised in Table 7, which defines the application framework of the RES scenario adopted in the present study.

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For each construction material, the table reports the adopted GWP fossil reduction factor together with the corresponding decarbonisation strategy and the main methodological assumptions supporting its application.

These factors constitute the basis for constructing the long-term renewable energy scenario adopted in the present study, which was subsequently adapted to the Italian context through the application of the temporal scenarios and diffusion rates described below.

Before applying these improvement factors, the methodological assumptions underlying the RES scenario were critically assessed in order to evaluate their applicability to the Italian production context and ensure a correct interpretation of the results.

The first aspect concerns the geographical representativeness of the electricity mix. The renewable electricity process modelled in SimaPro is based on a Swiss electricity mix, predominantly characterised by hydropower generation. By contrast, the Italian renewable electricity mix includes substantially higher shares of solar and wind energy, which may influence the results, particularly for energy-intensive construction materials. The authors themselves acknowledge this limitation and identify the development of country-specific models for individual Member States as an important direction for future research (Pristerà et al., 2026).

A second consideration relates to the implicit technological transition embedded in the steel production scenario. For steel, the RES scenario does not rely solely on the substitution of the energy carrier but also incorporates a transition from the Basic Oxygen Furnace (BOF) process to the Electric Arc Furnace (EAF) route, which is considered necessary to enable the complete electrification of steel production. Consequently, the reported −87% GWP fossil reduction reflects the combined effect of fuel switching and a change in the underlying production technology.

A final methodological consideration concerns the assumption that the total energy demand of each production process can be entirely supplied by renewable energy sources without affecting the overall energy demand of the process. As acknowledged by Pristerà et al. (2026), this assumption represents an idealised transition scenario and may not fully capture the technical and economic constraints associated with the decarbonisation of industrial production, particularly for high-temperature processes that still rely on direct fossil fuel combustion.

The diffusion rates developed within the European Commission DG GROW project (European Commission, 2025; Alaux et al., 2024) quantify, as a percentage, the share of the building stock in which each measure is effectively implemented within each Member State in a given reference year, taking into account structural constraints, industrial capacity, and the national regulatory context.

For the Italian context, input data from the PULSE-EU model were adopted using the CRS (Circular Reduction Strategies) scenario for the two reference time horizons considered in the project, 2030 and 2050. The adoption of these two time horizons makes it possible to represent a progressive decarbonisation pathway, allowing the comparison between a medium-term scenario, still constrained by the adaptation time required by the national production system, and a long-term scenario, which can be assumed as a more complete implementation of the proposed decarbonisation measures.

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Table 7: Scenario-based GWP fossil reduction factors and methodological assumptions adopted for the long-term assessment

Building Material	GWP Fossil Reduction	Decarbonisation strategy	Methodology assumptions
Aluminium	-80%*	Complete substitution of conventional energy sources with renewable electricity (Swiss electricity mix, ~98% hydropower)	Direct emissions from fossil fuel combustion are set to zero. No process-related CO_2 emissions independent of the energy source exist in aluminium production. A marginal overestimation of ~5 percentage points with respect to literature values is acknowledged
Clay brick	-85%*	Complete substitution of conventional energy sources with renewable electricity (Swiss electricity mix, ~98% hydropower)	Direct emissions from fossil fuel combustion are set to zero. Clay firing does not involve CO_2-releasing chemical reactions: all direct emissions are of energetic origin. A marginal overestimation of ~5 percentage points with respect to literature values is acknowledged
Concrete	-13%*	Complete substitution of conventional energy sources with renewable electricity throughout the production chain (clinker → cement → concrete)	The reduction is limited because CO_2 emissions from limestone calcination (~60% of clinker emissions) constitute an unavoidable process emission that cannot be eliminated through energy substitution alone. Only emissions attributable to fossil fuel combustion are set to zero
Glass	-64%*	Combined substitution with renewable electricity and biomethane. The reported value represents the average of the two sub-scenarios	The value is the average of two sub-scenarios (renewable electricity and biomethane). Direct emissions from fossil fuel combustion are set to zero. A sensitivity analysis removing all direct CO_2 emissions yields a reduction of ~81.5%; the adopted value is therefore conservative
Steel	-87%*	Renewable electricity combined with a transition from Basic Oxygen Furnace (BOF) to Electric Arc Furnace (EAF).	The reported reduction cannot be achieved through fuel switching alone applied to a conventional BOF process (sensitivity analysis: <−5% GWP fossil reduction). The value embeds a change in production technology, which also affects other environmental indicators (human toxicity, soil quality). It cannot be applied as a scalar factor to BOF-based processes without explicitly declaring the assumption of full technological conversion

* **Note:** The reported reduction factors refer to the fossil GWP of conventional production processes (modules A1–A3) and were obtained through LCA modelling performed in SimaPro 9.6.0.1 using the Ecoinvent 3.9 database (Pristerà et al., 2026). Within INDICATE LIFE, these factors were adopted as scenario-based improvement factors and weighted according to the diffusion rates defined for the CRS scenario (DG GROW; European Commission, 2025) for the 2030 and 2050 time horizons.

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Measure 5.3: Carbon capture, utilisation and storage in production

Carbon Capture, Utilisation and Storage (CCUS) technologies are increasingly recognised as one of the most promising solutions for reducing industrial GHG emissions from hard-to-abate sectors, where the high demand for thermal energy still limits the complete replacement of fossil fuels with renewable energy sources (IEA, 2019), as discussed under Measure 5.2. These technologies can follow two alternative pathways: the permanent geological storage of captured CO_2 (Carbon Capture and Storage – CCS) or its utilisation as a secondary resource in industrial processes (Carbon Capture and Utilisation – CCU), both encompassed within the broader CCUS framework.

In the concrete industry, for example, captured CO_2 can be used to accelerate the carbonation process during production, promoting the formation of stable calcium carbonate. However, considering the current state of industrial implementation and the available literature (Heidelberg Materials, 2024), the present study focuses exclusively on the application of CCS to cement production.

To evaluate its potential contribution to WLC reduction within the Italian context, two complementary approaches were developed:

1. Mapping of cement products available on the Italian market with an available EPD. The survey focused on CEM I, CEM II, and CEM III cements, which were used to define the baseline scenario. Starting from the corresponding GWP TOT values, a comparative assessment was performed for the production of 1 m^3 of generic concrete, comparing conventional cement mixtures with a hypothetical CEM-CCS scenario. The latter does not represent an existing product but a modelled scenario, obtained by reducing the emissions associated with clinker production (module A3) according to the CCS assumptions, while maintaining the remaining life-cycle contributions unchanged;
2. Remodelling of a representative case study, selected from the 50 case studies analysed within INDICATE LIFE IT, through the integration of an updated database representing the application of CCS to clinker production and its effect on concrete products. Within this scenario, the CO_2 emissions associated with clinker production (module A3) were assumed to be zero.

For the first approach, the main programme operators and their corresponding EPD platforms reporting cement products available on the Italian market were investigated. The survey identified three principal sources of information: EPD Italy, The International EPD System, and BAU EPD (Baustoffe mit Transparenz-EPD).

Product selection was based on the three main cement classes defined in EN 197-1:2011:

- CEM I (clinker content ≥ 95%);
- CEM II (clinker content between 65% and 95%);
- CEM III (clinker content between 5% and 64%).

Table 8 presents the survey results, along with the corresponding GWP TOT values for 1 m^3 of generic concrete (assumed density: 2,400 kg/m^3) produced using CEM I, CEM II, CEM III, and the hypothetical CEM-CCS scenario. The impacts associated with aggregates, water, and electricity consumption were calculated using generic datasets, whereas the impacts related to the transport of materials from the production site to the construction site were not considered.

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Table 8: Survey on national cement products covered by EPDs and potential reduction scenario based on CCS technology

Cement class	EPD mapped	Average GWP TOT for cement	Average GWP TOT for 1 m^3 of concrete	Average GWP TOT for 1 m^3 of concrete CEM-CCS	Percentage reduction from traditional mixture to CEM-CCS
Units	N°	$kgCO_2eq/kg$	$kgCO_2eq/m^3$	$kgCO_2eq/m^3$	%
CEM I	53	0,918	333,191	57,734	-82,67
CEM II	119	0,781	292,097		-80,23
CEM III	27	0,503	208,745		-72,34

The second approach consists of integrating CCS technology into the material database developed by the Italian consortium for the WLC assessment of the analysed case studies. This approach aims to evaluate the potential influence of CCS implementation on the environmental performance of representative buildings under a long-term decarbonisation scenario.

Although CCS is widely recognised as a key technology for supporting the decarbonisation of the Italian cement industry (Federbeton, 2025), its large-scale implementation still requires substantial technological and infrastructural developments. In particular, the deployment of CCS systems involves significant modifications to existing production plants, together with the development of a national network for the transport and permanent storage of captured CO_2. This includes the identification of suitable storage hubs and geological storage sites, whose long-term integrity and monitoring procedures are not yet fully standardised (CCSA, 2026).

A strategic framework for the deployment of industrial carbon management technologies has been outlined by the European Commission in the Communication "Towards an ambitious Industrial Carbon Management for the EU" (COM(2024) 62 final), which identifies CCS as one of the key enabling technologies for achieving climate neutrality in energy-intensive industries.

Considering the current technological, infrastructural, and regulatory challenges associated with CCS implementation in Italy, the scenario developed in the present study should be regarded as a long-term exploratory scenario, rather than a short-term deployment pathway. According to Federbeton (2025), a large-scale implementation of CCS within the Italian cement sector is not expected before 2050.

5.2.4. Strategy 6 description: Reduce emissions from transport of materials and construction products

WLC Strategy 6 aims to reduce WLC by addressing the emissions associated with the transport of construction materials and products to the construction site. To this end, it comprises the following two measures:

- **6.1 reducing the distance materials travel to construction sites by favouring local sourcing**
- **6.2 employing low-carbon transportation alternatives**

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Both measures primarily affect the LCMs associated with the transport of construction materials, with particular reference to module A4, which accounts for the transport of construction products from the manufacturing site to the construction site, although transport-related emissions may also occur in other LCMs.

More specifically, **Measure 6.1** aims to reduce transport-related emissions by shortening supply distances through local or regional sourcing, whenever technically and economically feasible. **Measure 6.2**, on the other hand, focuses on reducing the carbon intensity of freight transport through the adoption of lower-emission vehicles, alternative fuels, or transport systems characterised by lower carbon intensity.

Together, these two measures address both the spatial dimension of construction material supply chains and the environmental performance of the transport systems used for material delivery. Within the present study, both measures were assessed through quantitative modelling scenarios developed using the national material dataset. In particular, Measure 6.1 evaluates the effect of reducing supply distances of some materials, whereas Measure 6.2 analyses the contribution associated with the progressive decarbonisation of transport systems.

Measure 6.1: Reducing the distance materials travel to construction sites by favouring local sourcing

To assess the emission reduction potential associated with local material sourcing, selected construction products were identified for which the European sourcing scenario adopted in the baseline was replaced by a national sourcing scenario.

The assessment was developed considering two product categories: reinforcing bars for reinforced concrete and window systems. For both categories, the European sourcing scenario assumed in the baseline (1,500 km) was replaced by a national sourcing scenario characterised by an average transport distance of 300 km.

Reinforcing bars for reinforced concrete were selected because, according to the hotspot analysis carried out on the national case study dataset (D7.22), they represent one of the materials contributing most significantly to the environmental impacts of foundations and reinforced concrete structural elements. The proposed measure therefore consists of reducing the sourcing distance from 1,500 km, assumed in the baseline scenario, to 300 km, representative of a national supply chain. This assumption is supported by the structure of the Italian steel industry. Italy is one of the leading European producers of reinforcing bars, with production facilities distributed across the national territory and a particular concentration in the Brescia area (the so-called Steel Valley), which hosts one of the largest clusters of Electric Arc Furnace (EAF) mini-mills in Europe, alongside significant production capacity located in Veneto, Friuli Venezia Giulia, and southern Italy. This production structure makes a national sourcing scenario of 300 km not only representative of current market conditions but also consistent with the 2030–2050 planning horizons, during which the expected expansion of domestic EAF production capacity is anticipated to further strengthen the national supply chain.

A second product category considered is represented by window systems, which are common to all analysed case studies. In this case, the measure consists of reducing the sourcing distance from a European scenario (1,500 km) to a national scenario (300 km).

This assumption is supported by the structure of the Italian window manufacturing sector, characterised by a widespread national production capacity and a well-established supply chain distributed across the country. Recent industry reports confirm the strategic role of the domestic window manufacturing industry in

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meeting national demand and its ability to supply all the main frame typologies (PVC, aluminium, aluminium–wood, and timber) (UNICMI, 2026; CRESME 2026). The national sourcing scenario is therefore considered representative of the current organisation of the Italian supply chain and consistent with the expected strengthening of short supply chains promoted by European sustainability policies for the construction sector over the 2030–2050 period.

Measure 6.2: Employing low-carbon transportation alternatives

To analyse the emission reduction potential associated with the adoption of lower-emission transport solutions, two alternative modelling scenarios were developed:

1. **Adoption of EURO 6 vehicles.** The first scenario assumes the adoption of EURO 6 heavy-duty vehicles, representing the use of newer and lower-emission vehicles compared with those assumed in the baseline. Based on the adopted emission factors (EFs), this assumption results in a 10% reduction in the emission factor compared with the baseline value (Table 9);
2. **Implementation of the HDV Regulation.** The second scenario considers the expected effects of the regulatory framework introduced by Regulation (EU) 2024/1610, which amends Regulation (EU) 2019/1242 by strengthening the CO_2 emission performance standards for new heavy-duty vehicles (HDVs). In particular, the Regulation requires a reduction in the average CO_2 emissions of new HDVs of 45% during the period 2030–2034, 65% during 2035–2039, and 90% from 2040 onwards, compared with the 2019–2020 reference period. However, these targets apply exclusively to newly registered vehicles and therefore cannot be directly transferred to the circulating fleet as a whole. According to ACEA data (ACEA, 2025), annual truck registrations in Italy amounted to 27,709 vehicles in 2025, compared with a circulating fleet of approximately 978,039 trucks, with an average fleet age of around 19.2 years. This corresponds to an approximate annual fleet renewal rate of about 3%.

Based on these data, a **conservative 20% reduction** in the emission factor was assumed for **2030**. This assumption does not represent a direct application of the regulatory target to the entire circulating fleet, but rather an intermediate scenario accounting for the partial renewal of the vehicle fleet, the progressive technological improvement of newly registered vehicles, and the gradual **uptake of lower-emission transport solutions**.

Table 9: Emission Factors for 6.2 (i-ii) measures

Scenario	Year	Strategy	EF ($kgCO_2eq/t{\cdot}km$)	Improvement	Reference
Baseline	-	Lorry 16-32t EURO5	1.55E-04	-	Ecoinvent
EURO 6	2030	Lorry 16-32t EURO6	~1.40E-04	–10%	Ecoinvent
HDV Regulation	**2030**	Regolament HDV	~1.20E-04	**–20%**	Reg. UE 2019/1242 + ACEA fleet age data

Given its closer alignment with the current EU regulatory framework and its explicit reference to the medium-term decarbonisation targets for heavy-duty vehicles, the second scenario (HDV Regulation) was selected for the quantitative assessment of

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WLC Measure 6.2. This scenario was also considered more comprehensive, as the improvement in vehicle emission standards represented by the first scenario can be regarded as one of the technological pathways contributing to the achievement of the broader regulatory targets incorporated into the HDV Regulation scenario. Accordingly, a **20% reduction** in the **transport emission factor** relative to the baseline was assumed, taking **2030** as the reference year.

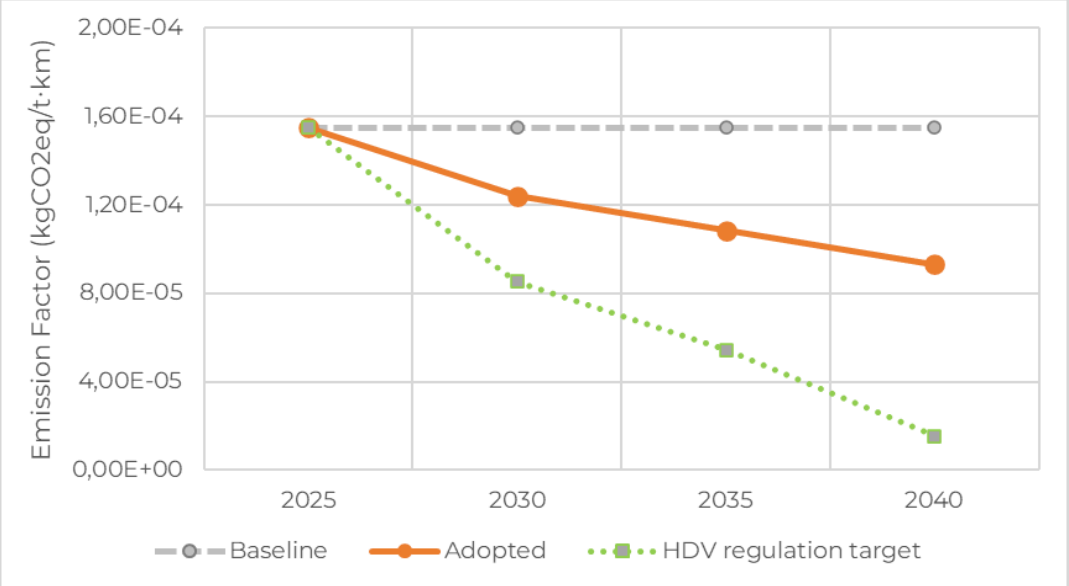


Figure 15: Reduction over time of the emission factor across the different scenarios

5.2.5. Strategy 8 description: Increase circular material use

WLC Strategy 8 aims to reduce WLC by increasing the use of recycled materials and the reuse of building components, thereby reducing the demand for virgin raw materials and the emissions associated with their production. To this end, it comprises the following three measures:

- 8.1 Re-use existing building components and materials
- **8.2 Use of materials with high recycled content**
- 8.3 Design for disassembly

As a whole, the strategy contributes to reducing the EC associated with modules A1–A3 through component reuse, increased recycled content, and design solutions that facilitate future material recovery.

More specifically, Measure 8.1 promotes the direct reuse of existing building components and materials, thereby avoiding the production of new elements. Measure 8.2 aims to increase the recycled content of construction materials, reducing the share of virgin raw materials required during manufacturing. Finally, Measure 8.3 addresses the design of buildings and building assemblies according to Design for Disassembly principles, facilitating the future recovery and reuse of components at the end of the building's service life.

Within the scope of the present assessment, only Measure 8.2 is quantitatively assessed in this report. Measures 8.1 and 8.3 are excluded for the following reasons:

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- Measure 8.1 cannot be assessed within the current modelling framework, as module D1 has not been characterised in the baseline. In the absence of a quantified D1 module, the environmental benefit of component reuse cannot be meaningfully isolated or attributed;
- Measure 8.3 was not further investigated, as its quantitative assessment would require the redesign of building assemblies and structural configurations to incorporate Design for Disassembly principles from the outset. Such an approach is not compatible with the methodology adopted in the present study, which is based on the assessment of existing case studies with fully defined material compositions and assembly configurations.

Measure 8.2: Use of materials with high recycled content

To assess the emission reduction potential associated with increasing recycled content, the main construction materials and their corresponding production chains were identified for which this strategy can reduce environmental impacts during the production stage (modules A1–A3).

The assessment was developed by comparing the recycled content values reported in the methodological documentation of the DG GROW project, the study by Pristerà et al. (2026), and the technical and environmental documentation available for the selected materials, including EPDs, Type II environmental declarations, and sector-specific technical documentation.

Table 10 summarises the comparison between the recycled content values reported by the different sources and the modelling assumptions adopted for each material.

Table 10: Comparison of recycled content values from different sources and the selected modelling assumptions

Reference	Glass	Steel	EPS	Clay brick
DG Grow	80%*	75%	-	-
Pristerà et al., 2026	80%	75%	-	-
Selected value	**64% (EPD Saint-Gobain)**	**75% (Pristerà, 2026)**	**60% (AIPE)**	**24% (EPD + label tipo 2-ICMQ)**

Based on the recycled content values adopted for each material, the corresponding GWP reduction factors were derived from the available technical and environmental documentation. The resulting values adopted for the assessment are summarised in Table 11. The methodological assumptions supporting the selected GWP reduction factors are discussed below for each material.

Table 11: GWP reduction factors adopted for the selected materials

Reference	Glass	Steel	EPS	Clay brick
DG GROW	-28%	-70%	-	-28%
Pristerà et al., 2026	-35%	-48%	-	-15%

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Selected value	-25%	-53%	-54%	-4.65%
*proxy estimate derived from an analogy with stone wool				

The GWP reduction factors reported in Table 11 were derived through a material-specific assessment based on the available technical and environmental documentation. The methodological assumptions supporting the selected values are described below for each material.

For **flat glass,** when closed-loop recycling was not feasible, the recycled content was assumed to originate from the building sector; only where this was not possible were alternative recycled sources considered. According to the adopted EPD (Saint-Gobain, 2023), pre-consumer recycled flat glass consists of manufacturing off-cuts and process losses generated during lamination, bending, and other processing operations, including the production of insulating glazing units and automotive windscreens.

Based on this documentation, a recycled content of 64% was adopted, compared with the 80% recycled content assumed by Pristerà et al. (2026). The adopted value corresponds to a 25% reduction in GWP, as reported in the Saint-Gobain EPD (2023).

The modelling approach adopted in the present study can therefore be considered more conservative than that proposed by Pristerà et al. (2026), who obtained a 35% reduction in GWP by explicitly modelling an 80% recycled content in flat glass production using the Ecoinvent process *"Flat glass, uncoated {RER} | flat glass production, uncoated | Cut-off, U"*.

The selected value is also consistent with the order of magnitude of the 28% GWP reduction reported in the DG GROW project. However, it should be noted that the DG GROW value was derived from a proxy estimate based on an analogy with stone wool, whereas the value adopted in the present study is based on product-specific environmental data for flat glass production. The differences between the reported values therefore reflect the different levels of specificity of the underlying datasets and modelling assumptions.

With regard to structural steel , a recycled content of 75% was adopted, consistently with the approach proposed by Pristerà et al. (2026). The modelling was carried out in SimaPro by incorporating the recycled material input into the corresponding Ecoinvent production process, which, under the baseline assumptions, did not include recycled content. This modelling approach resulted in a 53% reduction in GWP compared with the baseline process.

The resulting value is consistent with that reported by Pristerà et al. (2026), who obtained a 48% reduction in GWP under a comparable recycled-content scenario.

A different approach was adopted for expanded polystyrene (EPS). In this case, a recycled content of 60% was assumed, corresponding to the maximum recycled content currently considered technically achievable for the production of new EPS insulation products according to the AIPE Technical Handbook (AIPE, 2025).

The modelling was performed in SimaPro by incorporating the recycled material into the Ecoinvent production process adopted in the baseline. Under this assumption, the GWP associated with modules A1–A3 is reduced by 54% compared with the baseline material, which does not include recycled content in the production process.

A direct comparison with the studies by DG GROW and Pristerà et al. (2026) was not possible, as neither investigation includes EPS among the analysed materials. In the

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latter study, PVC was selected as the representative material for the plastics category, assuming a 69% substitution of virgin material with recycled content.

The definition of recycled content for clay bricks proved more challenging. Although the literature reports the possibility of partially replacing clay with different waste-derived materials (Mohajerani et al., 2018; Ramos Huarachi et al., 2020), none of these alternatives has yet become sufficiently established to be considered representative of current industrial practice.

For this reason, the present study adopted the recycled content reported for a typical Italian hollow clay block, based on an Italian third-party verified EPD (Type II ICMQ Environmental Label) (Stabila, 2026). The product is characterised by a recycled content of 29.5%, consisting of 16.5% production waste, 10.3% foundry sand, and 2.7% MRL.

The adopted modelling assumptions resulted in a 4.65% reduction in GWP compared with the baseline scenario.

Overall, the results indicate that increasing recycled content has the potential to significantly reduce the embodied impacts associated with material production, although the magnitude of the reduction varies considerably across materials depending on the characteristics of the production process and the recycled content currently achievable under industrial practice. The resulting GWP reductions adopted for Scenario 8.2 are summarised in Figure 16.

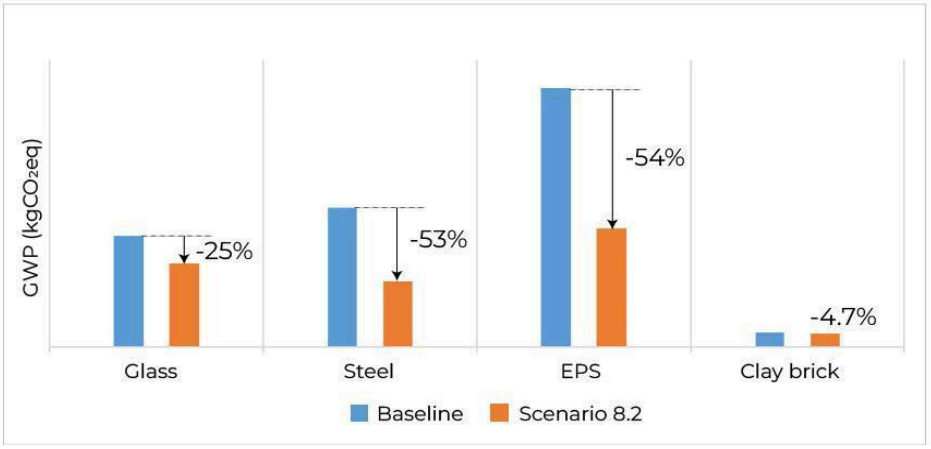


Figure 16: Material-specific GWP reduction associated with increased recycled content (WLC measure 8.2)

For **concrete**, recycled content may originate from different components of the product. The most common approach consists of replacing natural aggregates with recycled coarse and fine aggregates, although concrete recycling may also involve the production of new cementitious materials (Caro et al., 2024). In the DG GROW project, the reported reduction in fossil GWP refers exclusively to the use of recycled aggregates in concrete. Accordingly, the same approach was adopted in the present study.

In Italy, the partial replacement of natural aggregates with aggregates derived from industrial processes or the demolition of reinforced concrete structures has progressively become established, promoting the recovery and reuse of materials that would otherwise be destined for disposal.

However, according to the Sustainable Development Foundation and FISE Unicircular (Sustainable Development Foundation & FISE Unicircular, 2021), although the recovery rate of construction and demolition (C&D) waste in Italy has consistently remained

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above the regulatory target of 75%, only 7.2% of the recovered material is actually reused in the production of new concrete. Of this amount, 6.8% is used in non-structural applications, while only 0.4% is employed in structural concrete production (Unicircular, 2021).

These findings are further supported by the 13th Federbeton Sustainability Report, which estimated that, in 2021, the substitution rate of natural aggregates with recycled or industrial aggregates in concrete production was only 0.39% (Federbeton, 2022).

In addition to the use of recycled aggregates, a further strategy for reducing the environmental impacts of concrete consists of the progressive replacement of clinker with Supplementary Cementitious Materials (SCMs).

The **EN 197-5** standard, published in 2021, introduced composite and ternary cements characterised by a substantially lower clinker content. Subsequently, EN **197-6**, published in 2023, introduced the possibility of using recycled concrete fines as supplementary cementitious materials. Although these cements are not yet CE marked, they are permitted under **UNI 11104:2025**, subject to either a European Technical Assessment (ETA) or a National Technical Assessment Certificate (CVT), thus requiring an additional qualification procedure before their use.

The results obtained from the Italian LCA database (Sposato et al., 2025) indicate that cement production (module A1) accounts for approximately 75% of the total impacts associated with the production stage (modules A1–A3) of 1 m^3 of concrete.

Consistent with these findings, the Federbeton report identifies the progressive replacement of clinker through SCMs, summarised in Table 12, as one of the most realistic decarbonisation pathways for the Italian cement sector. Accordingly, the updated cement emission factors reported by Federbeton were adopted to remodel the baseline concrete mixes using the ARCADIA database and the corresponding mix design specifications.

Table 12: SCMs considered for clinker substitution and their expected availability in the Italian context

SCM	Expected availability over the 2030–2050 period	Current technical feasibility
Blast furnace slag	Slightly decreasing	High
Fly ash	Rapidly decreasing	High
Limestone	Stable	High
Pozzolan	Stable	High
Calcined clay	Increasing	Medium

Based on the High SCM scenario described in the Federbeton Sustainability Report, the corresponding reduction factors for the environmental impacts associated with cement production (modules A1-A3) were derived. The resulting values are summarised in Table 13.

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Table 13: Cement production pathway under the Federbeton High SCM scenario (2023–2050).

Parameter	2023	2030	2050
Production (Mt)	19	19	17
GWPtot/kg CEM	0,72	0,57	0,36

Accordingly, the emission factors reported in the Federbeton report were adopted to remodel the baseline concrete mixes using the corresponding mix designs and the ARCADIA database adopted in the present study. The resulting GWP values obtained for the analysed concrete mixes under the baseline, 2030, and 2050 scenarios are presented in Figure 17. The observed reduction reflects the progressive decrease in the carbon intensity of cement production, driven by the increasing substitution of clinker with SCMs under the High SCM scenario.

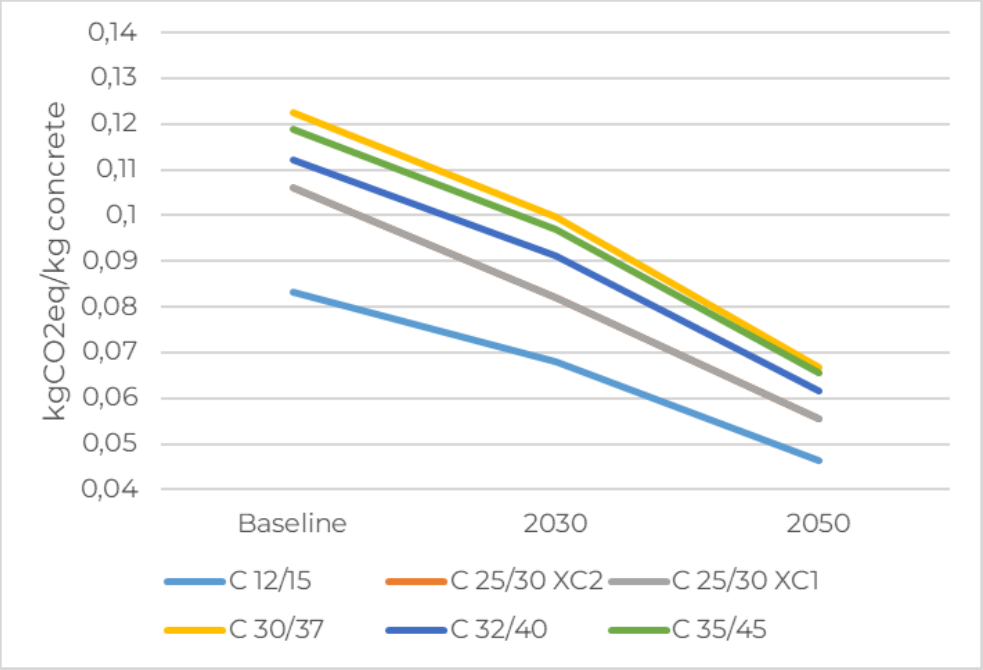


Figure 17: GWP reduction of the analysed concrete mixes under the High SCM scenario

5.2.6. Strategy 9 description: Reduce operational emissions

This strategy is broken down into several WLC measures, which are reported below:

- 9.1 Reduce energy for space heating and cooling
- 9.2 Reduce energy for ventilation
- 9.3 Reduce energy for water heating
- 9.4 Reduce energy for lighting
- 9.5 Increase renewable energy
- 9.6 Improve facility management
- 9.7 Include tenants.

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This strategy addresses the emissions associated with building energy use over the operational phase of the lifecycle, acting primarily on modules B6 (operational energy use) and, where on-site generation is present, on the interaction between B6 and the carbon intensity of the energy supply. The measures under this strategy span a wide range of interventions, from envelope and systems design optimisation (Measures 9.1–9.4) to renewable energy integration and facility management (Measures 9.5–9.7).

Measure 9.5 is the only measure under Strategy 9 assessed quantitatively in this report and is modelled at the scale of the Italian national electricity grid.

The remaining measures are excluded for the following reasons:

- Measures 9.1 through 9.4 would require a detailed reassessment of building mechanical and electrical systems (including heating, cooling, ventilation, and lighting installations), implying design-level interventions that extend beyond the characterisation of existing buildings. Such reassessment would also carry implications for architectural and envelope design, as modifications to technical systems are rarely independent of spatial and constructive choices. This level of intervention is not compatible with the case-study-based approach adopted in this project, where analyses are grounded in real, fully specified buildings whose design cannot be altered;
- Measures 9.6 and 9.7, addressing facility management and occupant behaviour respectively, depend on operational parameters that fall outside the scope of lifecycle modelling as implemented here, and cannot be reliably quantified from the available case study documentation;
- **Measure 9.5: Increase renewable energy.**

This measure focuses on the anticipated decarbonisation of the Italian national electricity grid, modelling alternative scenarios representative of the projected future energy mix. Rather than intervening at the level of individual building systems, the strategy operates at the scale of the electricity supply chain: the carbon intensity factor for module B6 (operational energy use) is updated to reflect the evolving composition of the national grid, as defined in official Italian energy planning documents.

In the baseline modelling, the electricity supply is characterised using the Ecoinvent process "Electricity, low voltage IT | electricity voltage transformation from medium to low voltage | Cut-off, U (2020)", which reflects the 2020 Italian grid mix. For the alternative scenario, this process is re-parametrised by the authors to incorporate the projected generation mix at the 2030 horizon, as detailed below.

The Piano Nazionale Integrato per l'Energia e il Clima (PNIEC) 2024 is the strategic document through which Italy defines its decarbonisation trajectory and ecological transition pathway to 2030. Adopted by the Ministry of Environment and Energy Security (MASE) in June 2024, it constitutes Italy's binding commitment under EU Regulation 2018/1999 on the Governance of the Energy Union and Climate Action. Its principal objectives include a substantial reduction in greenhouse gas emissions, an increase in renewable energy sources (RES) to cover 63.4% of gross inland electricity consumption, and a significant improvement in energy efficiency across the residential, commercial and industrial sectors. The Plan provides the analytical basis for aligning Italy's energy system with the European policy frameworks of the Fit for 55 package and REPowerEU.

The PNIEC projects a radical transformation of the Italian electricity generation system, driven by the electrification of end-use sectors and a large-scale expansion of renewable generation capacity. The key reference points are as follows:

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- **Baseline 2021** (Baseline): renewable sources covered approximately 36% of gross inland electricity consumption (325.1 TWh total);
- **2030 scenario** (PNIEC target): the renewable share in the electricity sector is projected to reach 63.4% of gross inland consumption (359.3 TWh total), corresponding to approximately 227.8 TWh of gross RES generation. In terms of gross total production, renewables would account for approximately 69% of 342 TWh (PNIEC 2024, p. 460);
- **2040 projection**: the renewable share is projected to grow further to 75% of gross total production (approximately 302 TWh out of 406 TWh total) (PNIEC 2024, p. 460). However, this horizon is not supported by source-disaggregated data - the PNIEC does not provide a breakdown by technology (hydro, wind, solar, etc.) equivalent to that available for 2030. Re-parametrisation of the SimaPro process at this horizon is therefore not feasible with the available data, and the 2040 scenario is excluded from quantitative modelling in this study.

The quantitative modelling is therefore limited to the 2030 scenario, for which disaggregated generation data by source are available in Table 12 of the PNIEC 2024 (MASE, p. 103). Table 14 reports the renewable energy growth targets for the electricity sector at 2030, as defined in the Piano Nazionale Integrato per l'Energia e il Clima.

Table 14: Targets for increasing the renewable energy share by 2030, as set out in the PNIEC 2024 (MASE, June 2024)

SCM	2021	2030
Gross electricity generation from RES	**118,7**	**227,8**
Hydropower (actual)	45,4	-
Hydropower (normalised)	48,5	46,9
Wind power (actual)	20,9	
Wind power (normalised)	20,3	64,8
Geothermal	5,9	7,5
Bioenergy	19	10,9
Solar	25	97,6
Gross inland electricity consumption	**329,8**	**359,3**
RES-E share	**36%**	**63,4%**

The re-modelling carried out within this measure acts exclusively on the OC of the case studies, replacing the baseline electricity emission factor (derived from the Ecoinvent process for the current Italian grid mix) with a re-parametrised value

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reflecting the projected 2030 national generation mix. The results therefore capture the decarbonisation benefit attributable solely to the evolution of the electricity supply carbon intensity. It should be noted, however, that the magnitude of this improvement is inherently dependent on the energy supply configuration of each individual case study: buildings relying predominantly on grid electricity will show the greatest sensitivity to this measure, while those whose operational energy demand is met through other energy vectors, such as on-site photovoltaic generation, district heating networks, or gas-fired heating systems, will reflect a more limited or negligible effect. This variability is structural and should therefore be taken into account when interpreting cross-typology differences in the results.

5.2.7. Strategy 10 description: Reduce construction and demolition waste

WLC Strategy 10 addresses the management of construction and demolition waste as a key pathway for reducing WLC. The reference framework comprises the following three measures:

- 10.1 On-site waste material sorting and separation
- 10.2 Reduce construction packaging
- 10.3 End of Life audits and waste audits.

In addition to the measures included in the reference framework, the methodological approach developed in the present analysis introduces an additional measure: **10.4 Improved end-of-life scenarios.**

The measures act across different life-cycle stages and modules, influencing the management of construction and demolition waste from its generation through to its recovery and final disposal. More specifically, Measure 10.1 promotes improved management of waste generated during construction activities (A5w and C1), with potential implications for waste recovery and disposal processes (C3–C4).

Measure 10.2, instead, aims to reduce the amount of packaging associated with construction materials, products, and components delivered to the construction site (A5 and B2–B4), thereby reducing the environmental impacts associated with their treatment and disposal (C4). Measure 10.3 requires the implementation of end-of-life and waste audits to verify the correct allocation of waste streams to landfill or recovery facilities. This measure contributes to improving the carbon balance associated with modules A5w, B2–B4, and C3–C4. Finally, Measure 10.4 investigates how improved end-of-life waste management can influence the overall WLC balance by modifying waste treatment and disposal scenarios (C3–C4 and D1).

Within the present study, only Measure 10.4 was further investigated, whereas Measures 10.1–10.3 were not assessed for the following reasons:

- Measure **10.1.** The modelling assumptions adopted for modules A5w and C1 (**D7.20**) do not allow the characterisation of waste collection and on-site sorting processes.
- Measure **10.2.** The assumptions adopted for the assessment of modules A5w and B2–B4 do not account for waste associated with the packaging of

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construction materials, products, and components. Consequently, the GWP associated with the recovery and disposal of packaging waste (C3–C4) cannot be quantified. Furthermore, reducing construction packaging requires systemic changes involving both manufacturing processes and transport logistics, which cannot be adequately assessed within the scope of the present study.

- Measure **10.3.** Although end-of-life and waste audits are recognised as valuable instruments for improving the circularity of building demolition and renovation activities, their quantitative assessment is not compatible with the methodological framework adopted in the present study. As described in **D7.20**, the baseline was developed using default end-of-life assumptions applied consistently across all case studies, based on waste family classifications. This approach, while ensuring methodological consistency across the dataset, does not capture the building-specific waste composition and material quantities that a waste audit would produce. The granularity of information required to model the effect of an audit is not available for the case studies considered in the present analysis.

Measure 10.4: Improved end-of-life scenarios

A qualitative assessment was conducted for this WLC measure. The objective was to identify revised end-of-life allocation percentages (across recycling, landfill, and incineration) that reflect anticipated future waste management practices, while maintaining the material family classification adopted for the baseline and described in **D7.20**.

For each material family, future end-of-life scenarios were derived from authoritative European sources, including industry roadmaps, EU policy targets, and sector-specific decarbonisation strategies. The methodology consisted of three sequential steps.

The first step consisted of identifying the material families with the greatest potential for improving end-of-life management. Not all waste families were considered eligible for end-of-life scenario revision. A preliminary screening was therefore conducted to identify those material families for which a meaningful improvement in recycling or recovery rates was considered technically feasible and supported by documented European trajectories. Material families already characterised by recycling rates approaching their technical potential were excluded from the analysis. Conversely, material families characterised by high landfill shares or low recycling rates, and for which sector-specific or analogous roadmaps were available, were retained for further assessment. The selected material families are reported in Table 15.

The second step consisted of defining revised end-of-life scenarios for each selected material family. Revised allocation percentages were derived from authoritative European sources, including industry decarbonisation roadmaps, EU policy targets, and sector-specific circularity strategies. Table 15 reports the revised allocation percentages alongside the baseline values, enabling a direct comparison. Where the available documentation referred primarily to sectors other than construction (e.g. road infrastructure), the applicability of the proposed end-of-life scenarios to construction and demolition waste streams was explicitly considered.

The third step consisted of assessing the applicability of the sources used to derive the revised scenarios. Given the heterogeneous nature of the available references, a qualitative indicator describing their applicability to the construction sector was assigned to each material family. The indicator is expressed using a three-level classification: **Level A** identifies sources explicitly addressing construction and

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demolition waste streams; **Level B** refers to sources covering the relevant material across multiple sectors, including construction; and **Level C** identifies sources referring to analogous materials or comparable waste management contexts outside the construction sector, adopted only in the absence of construction-specific information. This classification supports the interpretation of the revised scenarios by providing an indication of the robustness of the underlying assumptions.

Table 15: Comparison between baseline and future end of life scenarios

Waste family	End of life (baseline)			End of life (future)			Level	Source
	Recycling	Landfill	Incineration	Recycling	Landfill	Incineration		
Inert waste	82,00	11,00	0,00	100,00	0,00	0,00	A	(1)
Non-ferrous metal	68,11	31,45	0,00	90,00	10,00	0,00	A	(2)
Bitumen	0,00	100,00	0,00	70,00	30,00	0,00	C	(3)
Plastics	6,70	63,60	29,70	35,00	19,00	46,00	B/C	(4)
Fossil based insulation	6,70	63,60	29,70	27,00	0,00	73,00	A/B	(1)
Gypsum board	82,00	11,00	0,00	95,00	5,00	0,00	A	(1)
Glass	78,16	21,68	0,00	97,00	0,00	0,00	A	(1)

(1) Cristóbal García, J., Caro, D., Foster, G., Pristerà, G., Gallo, F., Tonini, D. (2024). Techno-economic and environmental assessment of construction and demolition waste management in the European Union. Publications Office of the European Union. https://doi.org/10.2760/721895

(2) European Aluminium. (2020). Circular Aluminium Action Plan: A strategy for achieving aluminium's full potential for circular economy by 2030. https://european-aluminium.eu/wp-content/uploads/2022/08/european-aluminium-circular-aluminium-action-plan.pdf

(3) European Asphalt Pavement Association (EAPA). (2026). Asphalt in Figures 2024. https://eapa.org/asphalt-in-figures/

(4) VinylPlus. (2025). Progress Report 2025 https://www.vinylplus.eu/our-achievements/progress-report-2025/pathway-1/

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A preliminary remodelling attempt was carried out within the declared system boundary (modules **C3–C4**). The results consistently showed an increase in GWP impact under the improved end-of-life scenarios, primarily attributable to the higher energy intensity of material preparation for recycling processes in module **C3**, compared with the landfill-dominated baseline. This outcome is structurally expected: within a **C3–C4** system boundary, increased recycling rates inevitably entail higher processing burdens, while the associated avoided burden (i.e. the substitution of virgin material production) is accounted for exclusively in **module D**, which lies outside the declared system boundary adopted in the present study.

Consequently, the full environmental benefit of improved end-of-life management cannot be quantified within the current assessment boundary. The measure is therefore retained as a qualitative contribution, providing a reference framework of future end-of-life scenarios consistent with European decarbonisation trajectories. A complete assessment of this measure would require the inclusion of **module D** within the system boundary, as recommended by **EN 15978** for studies in which end-of-life recycling represents a significant system variable.

5.2.8. Strategy 11 description: Use of carbon dioxide removal (CDR) solutions

The following WLC measures are included under Strategy 11:

- **11.1 Green roofs and/or green facades**
- 11.2 Increased use of biochar
- 11.3 Direct Air Capture (DAC)

This strategy addresses processes, systems, and technologies capable of capturing and storing atmospheric CO_2, thereby reducing the overall WLC balance. Measure 11.1 exploits the natural capacity of vegetation, through chlorophyll photosynthesis, to convert CO_2 and water into glucose and oxygen; its application at building scale may entail increased impacts associated with the installation of the green roof technological package or of a Living Wall System (LWS), alongside a reduction attributable to the photosynthetic process, quantifiable within module B1 (analogously to the treatment of carbon uptake in lime- and cement-based products, with reference to Sub-module B1.2 of the forthcoming EN 15978:2026). Measure 11.2 investigates the integration of biochar into building materials such as concrete, mortars, and plasters; biochar is produced through the pyrolysis of biomass waste (including agricultural residues, wood, and sewage sludge) under oxygen-limited conditions, converting organic carbon into a highly stable crystalline form and thereby acting on the production stage (A1–A3) by embedding a carbon-sink aggregate into construction materials. Measure 11.3 concerns active carbon capture technologies applied at building scale; Direct Air Capture (DAC) is used here as a general term encompassing Carbon Capture and Storage (CCS) and Carbon Capture, Utilisation, and Storage (CCUS) systems, which may operate either at the production stage (A1–A3, as addressed under Strategy 5) or during building use (B1), through the integration of DAC sorbents or nanofibre filters into existing HVAC systems, or through the use of building facades as carbon-absorbing surfaces employing materials other than LWS.

Notwithstanding relevant international research on biochar (Kang et al., 2026; Kang et al., 2025; Mishra et al., 2022) and of DAC technologies (Wu et al., 2025; Baus & Nehr,

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2022), the authors have elected not to pursue the quantitative assessment of Measures 11.2 and 11.3.

This decision is grounded in two considerations: first, neither technology is currently documented at an industrial scale within the national context; second, the available international data remain insufficient to justify a modification of the material database developed by the Italian consortium.

With respect to Measure 11.1, one case study includes a green roof that was designed and constructed. Specifically, the renovation project for the residential building coded IT_MFH_11_R_E_3 includes a green roof of approximately 813 m^2. The system is a lightweight intensive green roof with grass carpet, comprising water-retention felt, mechanical protection layer, a combined water-retention, drainage, and aeration layer, a filter membrane, and a growing substrate, conforming to the requirements of UNI 11235:2015 (*Guidelines for the design, construction, inspection and maintenance of green roofs*). The total system thickness is 25 cm ± 5%, with a substrate thickness of 20 cm after compaction, a maximum weight at full water saturation (excluding vegetation) not exceeding 282 kg/m^2, and a maximum water retention capacity of MT ≥ 92 l/m^2. The GWP associated with the installation of this system has already been assessed; the present analysis extends the assessment to include the CO_2 absorption benefit attributable to the vegetated layer.

Within the LCA and WLC assessment framework adopted for this project, the carbon sequestration benefit of vegetation (whether in green roofs or LWS) is accounted for in module B1. However, in accordance with the national methodology described in **D7.19** (Palumbo et al., 2026), module B1 is treated as a recommended rather than mandatory module for the Italian consortium, and its contribution has not been included in any of the case study reports. Measure 11.1 therefore represents an extension of the standard assessment scope.

To quantify the B1 carbon absorption for IT_MFH_11_R_E_3, two sources representative of the Italian context were consulted: Andreotti and Giordano (2024), which estimates CO_2 absorption at −2.5 $kgCO_2/m^2/year$ for extensive green roofs and −2.0 $kgCO_2/m^2/year$ for LWS; and the DAKU Italia life-cycle report (DAKU & MR Energy System, 2021), which reports absorption values of −2.460 $kgCO_2/m^2/year$ for extensive systems and −1.232 $kgCO_2/m^2/year$ for intensive systems. For this case study, the value of **−1.232 $kgCO_2/m^2/year$** was selected as the reference absorption rate for an intensive green roof, multiplied by the roof area (813 m^2) and the reference study period (**50 years**), yielding a total B1 module input value of **−50,080.8 $kgCO_2$** for the WLC model.

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6. Results of the assessment

This chapter presents the **results** of the WLC measures assessed through a **quantitative approach**, following the methodological implementation described in the previous chapter. The objective is to report the effects of the remodelling activities in a consistent and comparable format, highlighting the variation in WLC impacts relative to the baseline scenario.

The results obtained are then compared with the baseline scenario in order to quantify the environmental benefit associated with each measure and assess its contribution to the reduction of WLC impacts.

Broader considerations regarding the interpretation of the results, the related uncertainties, and the role of the different measures within the overall WLC reduction pathway are discussed in Chapter 7.

6.1. Result reporting format

To ensure consistency in the presentation of the different strategies and full traceability of the results, a **common reporting format** was defined for the WLC measures assessed quantitatively within the project. This format, schematically illustrated in **Figure 20**, organises the information using a consistent structure, allowing the assessments carried out for the different measures to be compared.

The format first introduces the WLC strategy considered, reporting the title of the strategy (Box A in Figure 20) and the related WLC measures assessed quantitatively.

Results are then reported by LCM and compared with the baseline scenario, in order to quantify the variation introduced by the measure and identify which parts of the assessment are most affected by the modelling assumptions adopted (Box B in Figure 20).

In addition to the module-by-module comparison, the relative contribution of each LCM to the overall improvement is reported as a percentage. This provides a complementary interpretation of the results, highlighting not only the magnitude of the variation compared with the baseline, but also the relative weight of the different modules in achieving the overall reduction of WLC impacts (Box C in Figure 20).

Finally, the results are discussed in a dedicated chapter (7), with the aim of highlighting the main trends observed, the most relevant changes compared with the baseline scenario and the contribution of the measure to the overall WLC reduction pathway.

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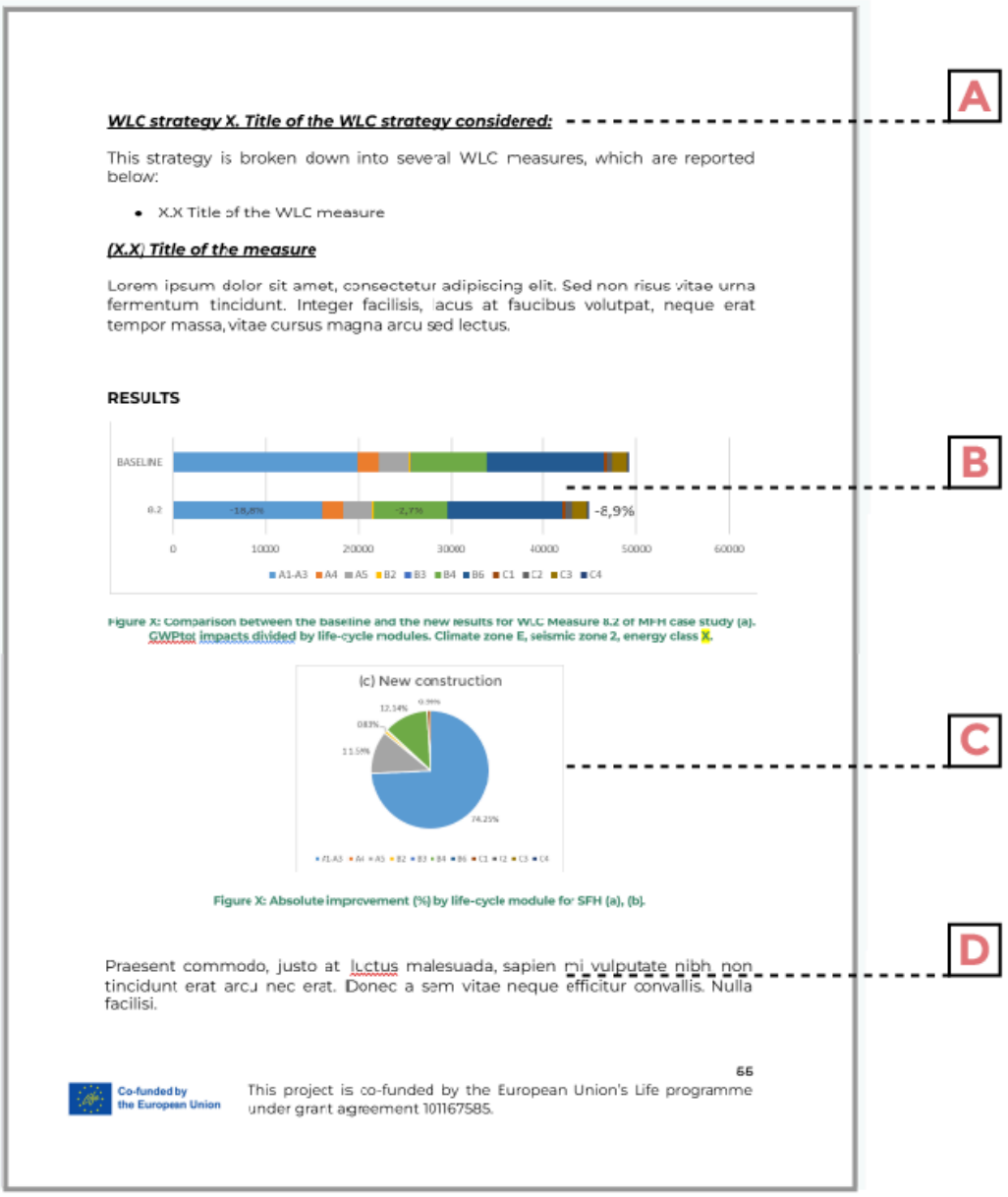


Figure 20: Reporting format adopted for the results of WLC measures assessed quantitatively

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6.2. WLC Strategies Results

6.2.1. Strategy 2 results. Prioritise better use, renovation and repair over demolition and new construction

This section presents the assessment results for the WLC measure analysed under Strategy 2, "Design for durability and maintainability of building components." This measure, introduced by the authors as an additional WLC measure, is subdivided into Measures 2.4.a and 2.4.b.

Assessment results for the additional WLC measure 2.4: Design for durability and maintainability of building components

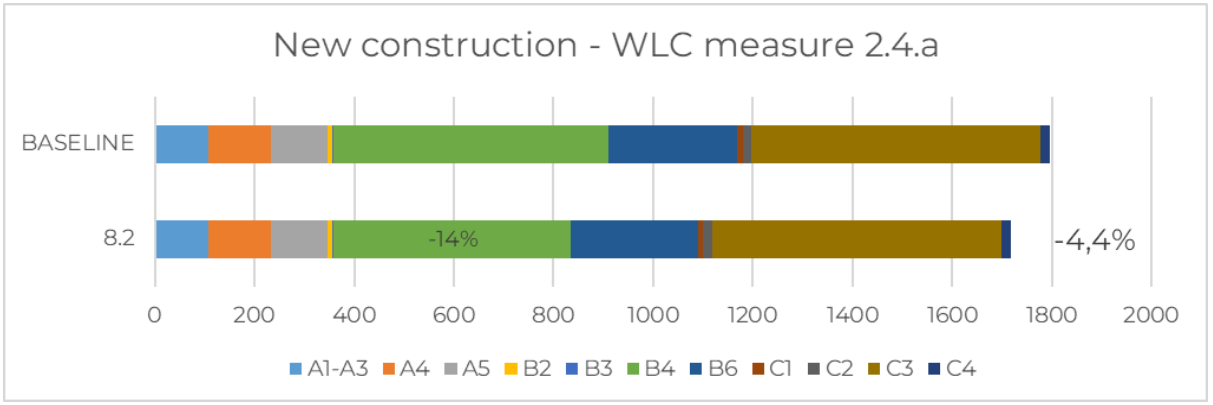


Figure 21: Comparison between the baseline and the new results for WLC Measure 2.4.a for a MFH case study. GWP_{tot} impacts divided by LCMs. Climate zone E, seismic zone 3

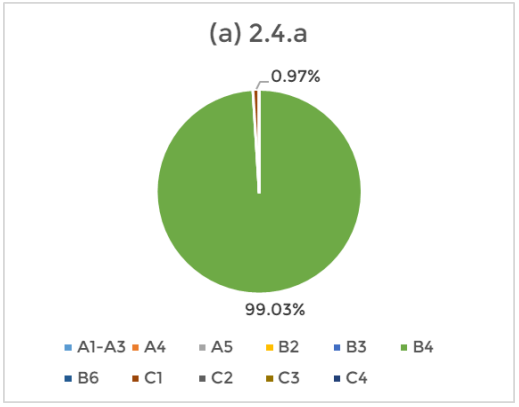


Figure 22: Absolute improvement (%) by LCM for WLC measure 2.4.a

The application of Measure 2.4.a to the case study produces measurable GWP reductions concentrated in module B4, which records a decrease of 14%. This improvement derives from the methodological disaggregation of composite building components (specifically the separation of the metal substructure from the gypsum board layer), which corrects the conservative service life assumption applied at category level in the baseline. The achieved reduction in B4 translates into a 4.4% reduction in total WLC.

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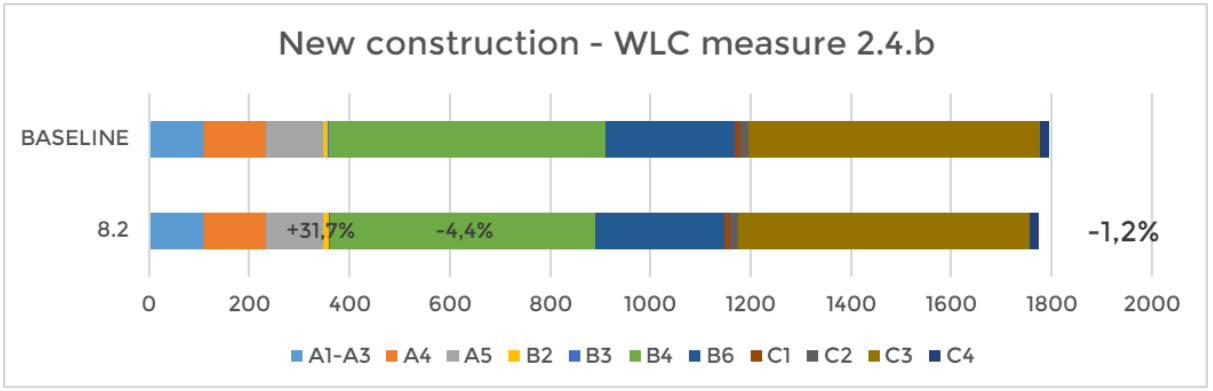


Figure 23: Comparison between the baseline and the new results for WLC Measure 2.4.b for a MFH case study. GWPtot impacts divided by LCMs. Climate zone E, seismic zone 3

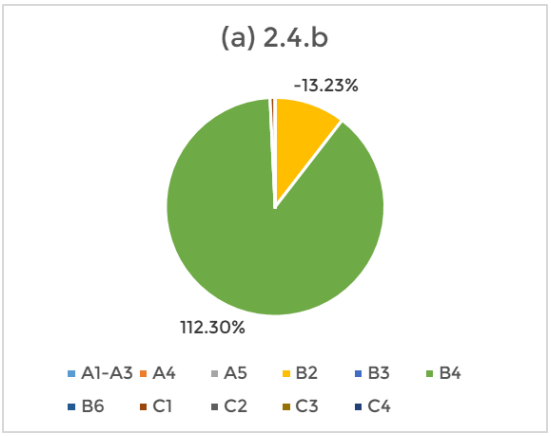


Figure 24: Absolute improvement (%) by LCM for WLC measure 2.4.b

The application of Measure 2.4.b to the case study produces a targeted redistribution of embodied impacts across lifecycle modules: module B4 records a reduction of −4.4%, while module B2 increases by +31.7%, reflecting the additional embodied contribution of the programmed maintenance intervention modelled as a single repainting coat at year 10. The net effect on total WLC is a reduction of −1.2%.

6.2.2. Strategy 5 results: Reduce emissions from traditionally high impact construction materials

This section presents the assessment results for the WLC measures analysed under Strategy 5, with a focus on the reduction of emissions associated with the production of traditionally high-impact construction materials. The analysis includes two measures: 5.2 Renewable energy sources in production and 5.3 Carbon capture, utilisation and storage in production.

For both measures, the results compare the baseline WLC impacts with the impacts obtained after the implementation of the selected decarbonisation option. The results are reported by building typology, reference year and LCM, in order to highlight where the main reductions occur and how the effects vary across the assessed cases.

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For WLC measure 5.2, the assessment is developed for the 2030 and 2050 horizons and covers the SFH, MFH and OFF typologies. For WLC measure 5.3, the analysis focuses on the application of carbon capture, utilisation and storage to cement production, highlighting its effects on the modules most directly influenced by material production processes.

Assessment results for WLC measure 5.2: Renewable energy sources in production

For WLC measure 5.2, the results are reported for the three assessed typologies: SFH, MFH and OFF. For each typology, the comparison between the baseline scenario and the scenario resulting from the application of the measure is developed for the 2030 and 2050 horizons, with reference to GWPtot impacts across the different LCMs. The results for SFH are reported in Figures 25–29, those for MFH in Figures 30–34, while the results for office buildings are reported in Figures 35–39.

SFH

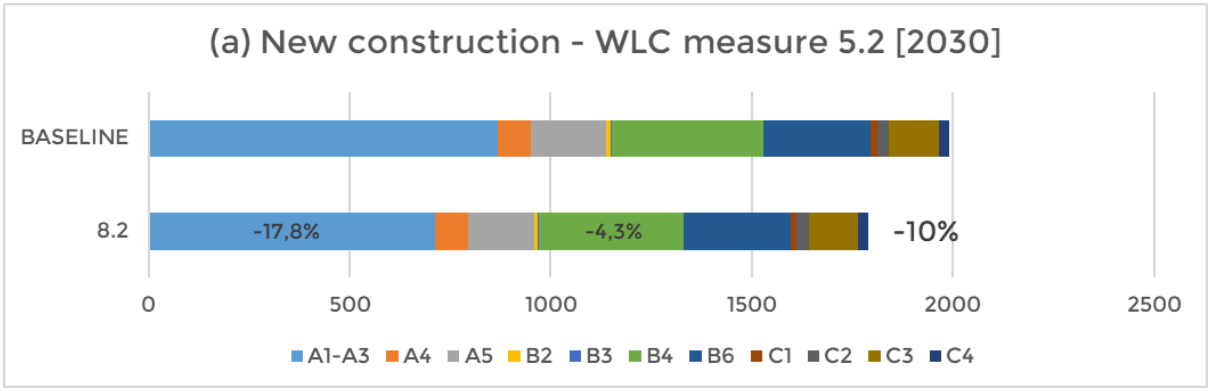


Figure 25: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the SFH case study (a). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

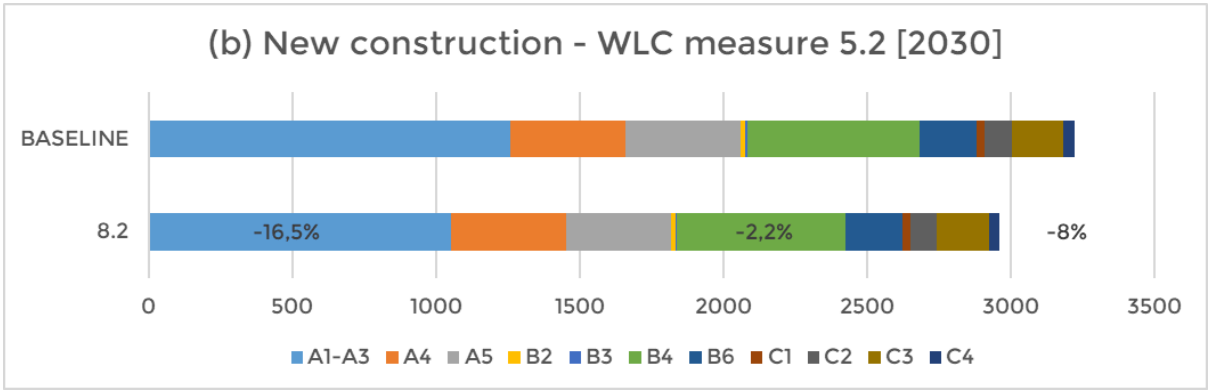


Figure 26: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the SFH case study (b). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

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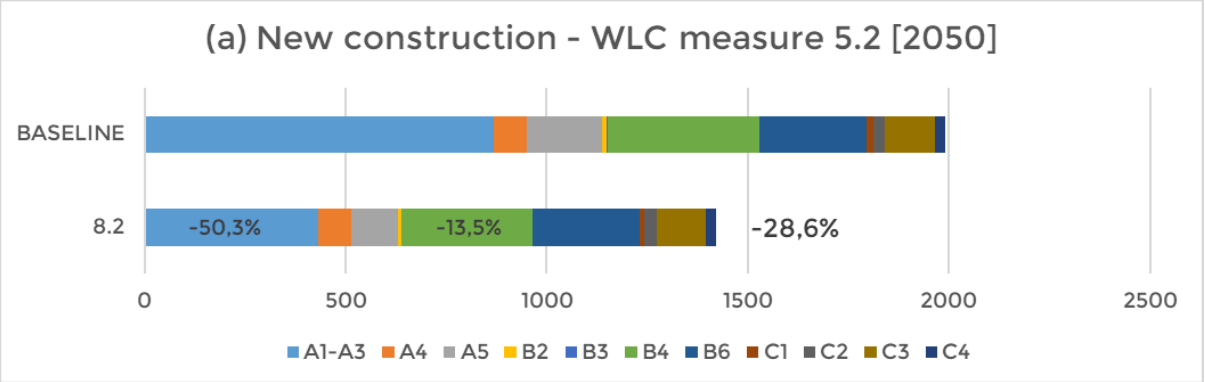


Figure 27: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the SFH case study (a). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

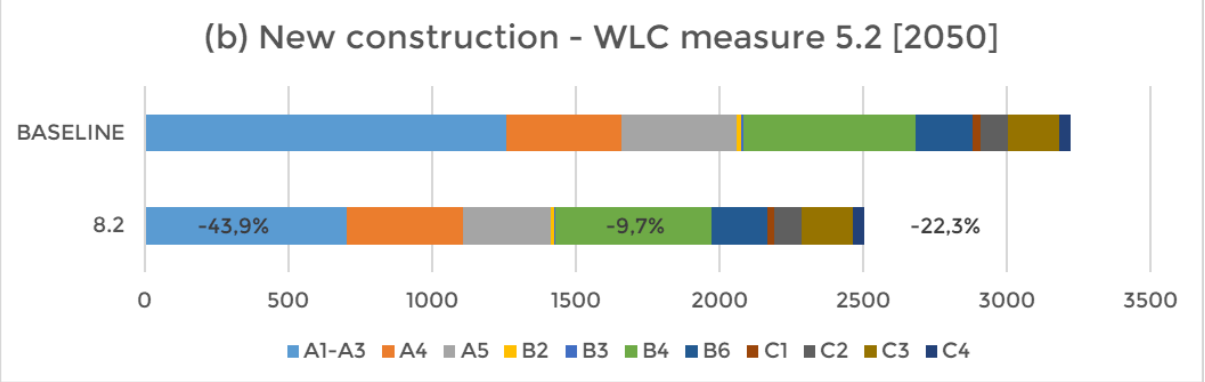


Figure 28: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the SFH case study (b). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

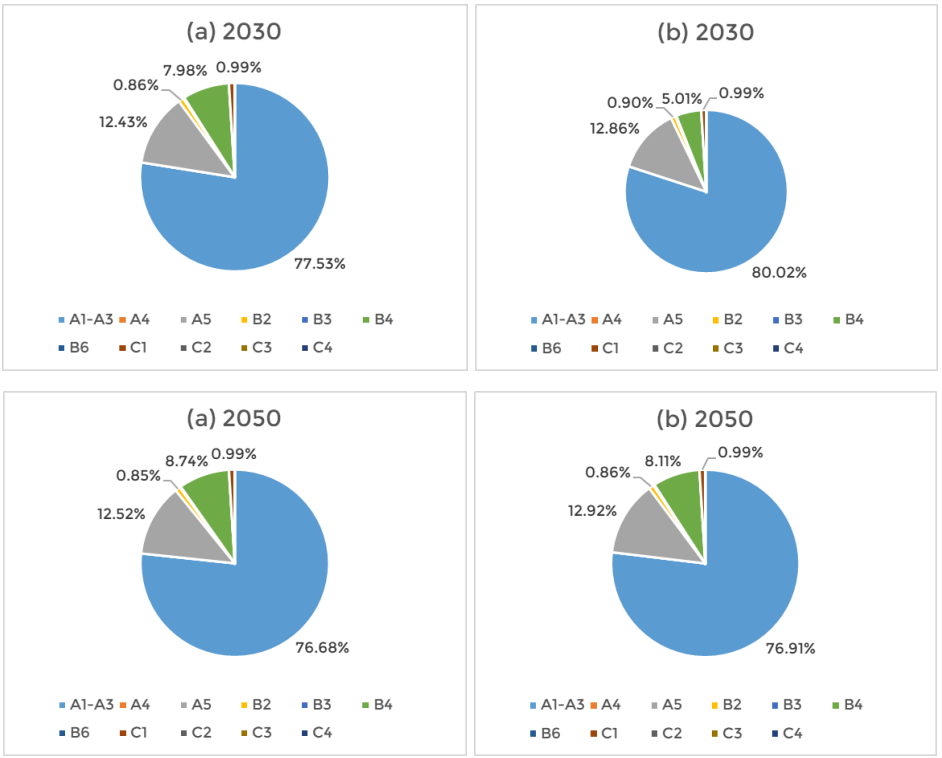


Figure 29: Absolute improvement (%) by LCM for SFH (a), (b) for 2030, 2050

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For the **SFH** typologies, the results indicate that the reductions are mainly concentrated in module A1-A3, consistently with the scope of the measure, which acts on material production processes. At the 2030 horizon, the impact of module A1-A3 is reduced by approximately 17–18%. Lower reductions are observed in module B4, equal to 2–4%, while modules B2 and B3 show reductions ranging from 13% to 16%. The overall WLC GWP reduction is 8–10%. At the 2050 horizon, the results show higher reductions, in line with the higher diffusion levels assumed for the measure. Module A1-A3 records a reduction of 44–50%, module B4 of 10–13%, while reductions in modules B2 and B3 range from 34% to 44%. The overall WLC GWP reduction ranges from 22% to 29%.

MFH

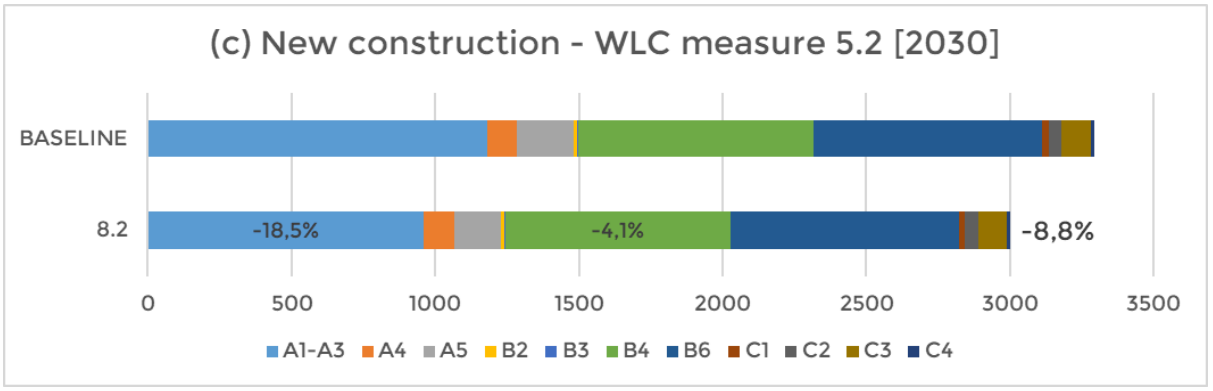


Figure 30: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the MFH case study (c). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

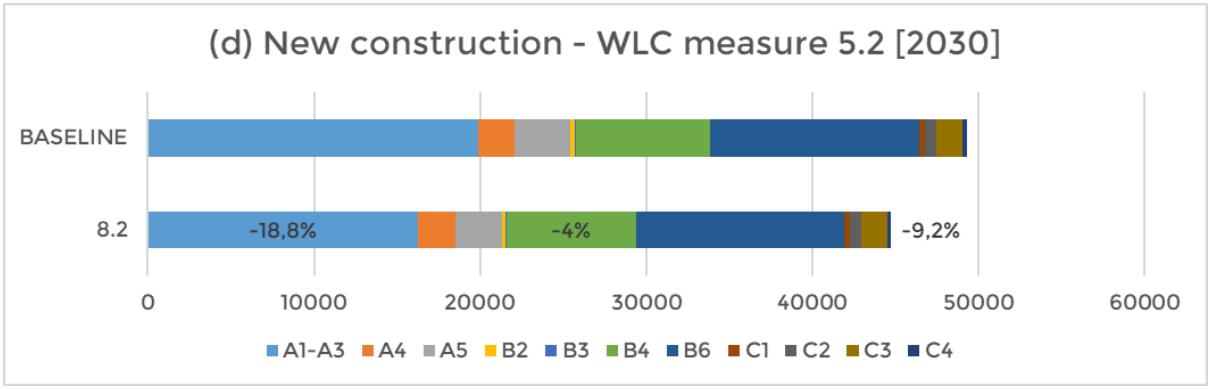


Figure 31: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the MFH case study (d). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

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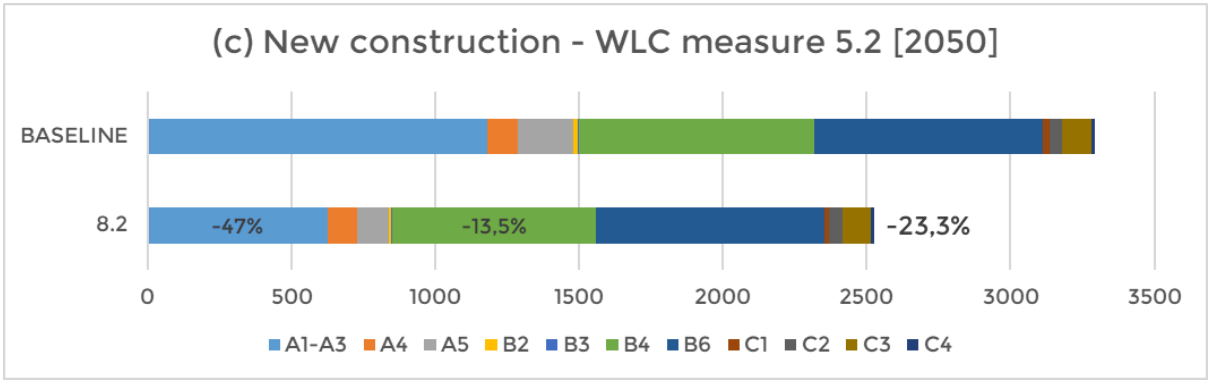


Figure 32: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the MFH case study (c). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

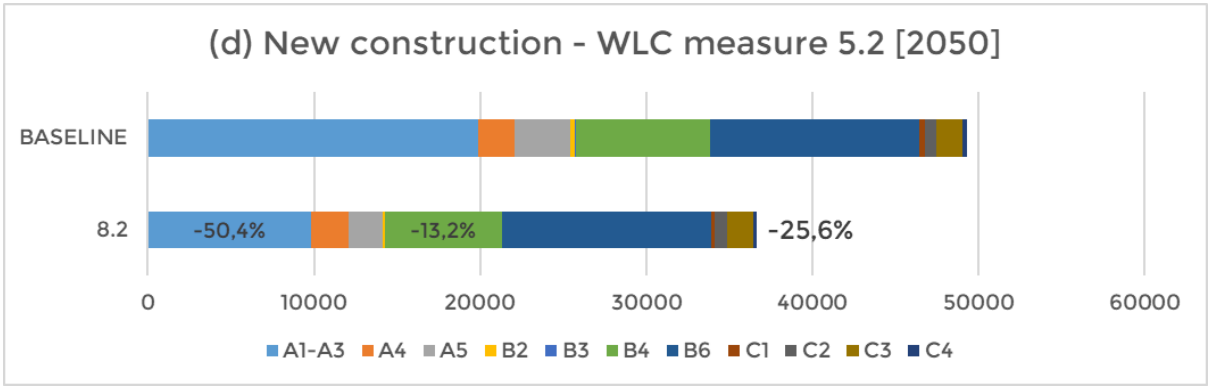


Figure 33: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the MFH case study (d). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

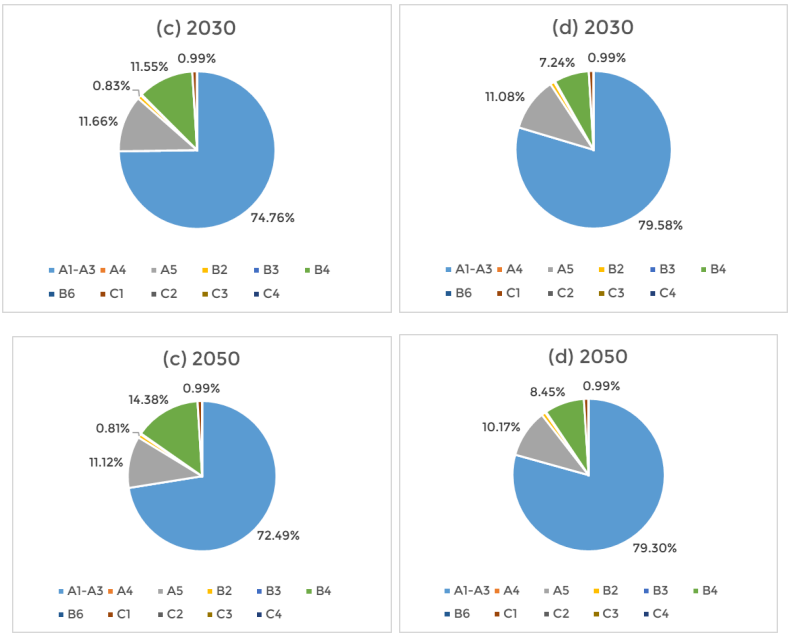


Figure 34: Absolute improvement (%) by LCM for MFH (c), (d) for 2030, 2050

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For the MFH typologies, Figures 30–34 indicate a trend substantially aligned with that observed for the SFH typologies. The reduction in module A1-A3 is approximately 18% at 2030 and increases to 47–50% at 2050. Module B4 is reduced by 4% at 2030 and by approximately 13% at 2050, while the reduction in modules B2-B3 increases from approximately 17% to 43–46%. The overall WLC GWP reduction is 9% at 2030 and ranges from 23% to 26% at 2050.

OFF

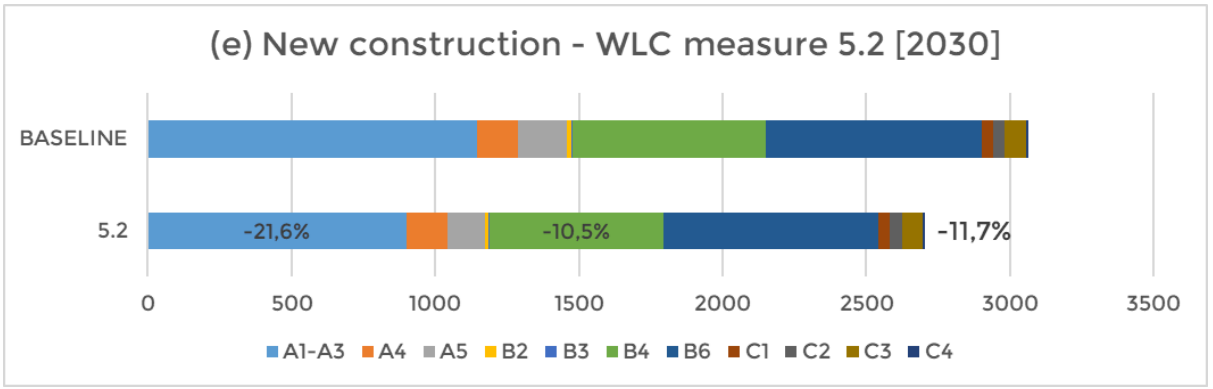


Figure 35: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the OFF case study (e). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 3

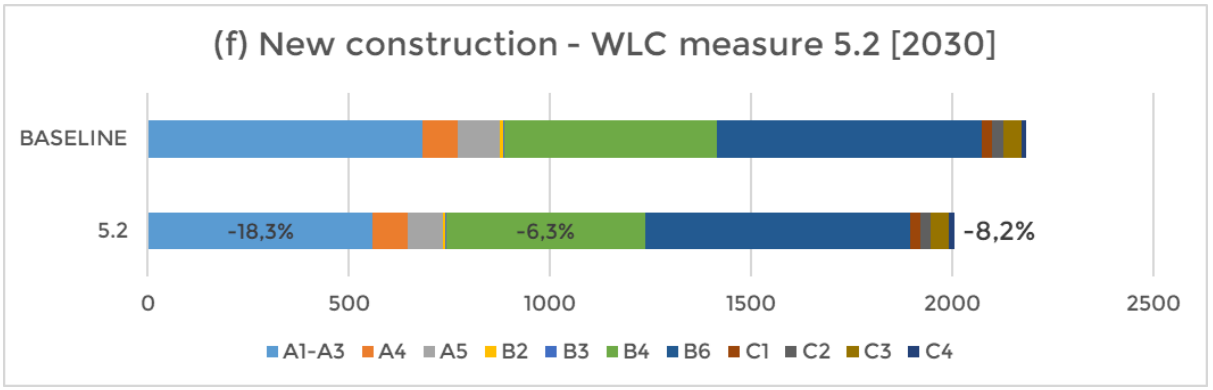


Figure 36: Comparison between the baseline and the new results for WLC measure 5.2 to 2030 of the OFF case study (e). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 3

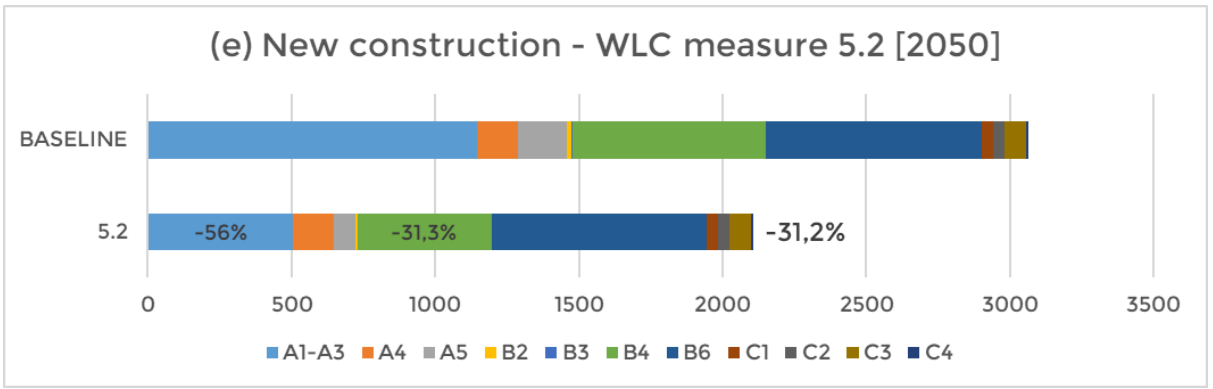


Figure 37: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the OFF case study (e). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 3

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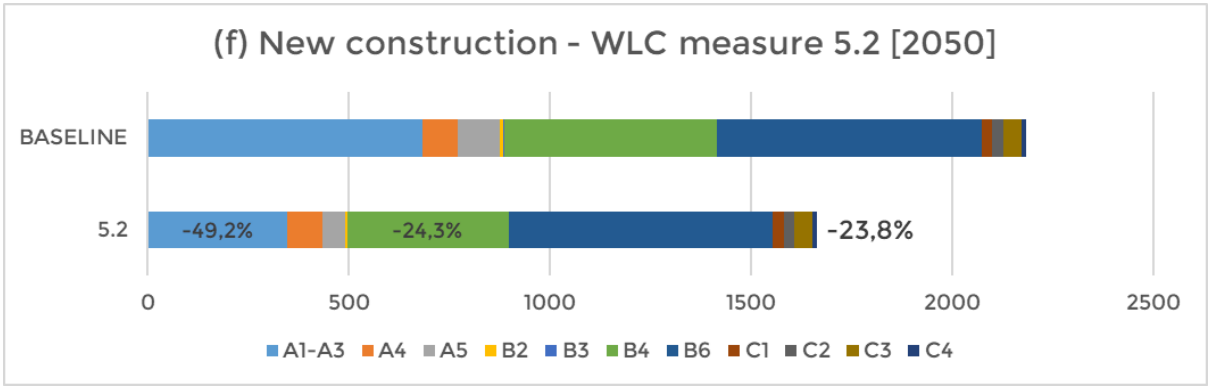


Figure 38: Comparison between the baseline and the new results for WLC measure 5.2 to 2050 of the OFF case study (e). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 3

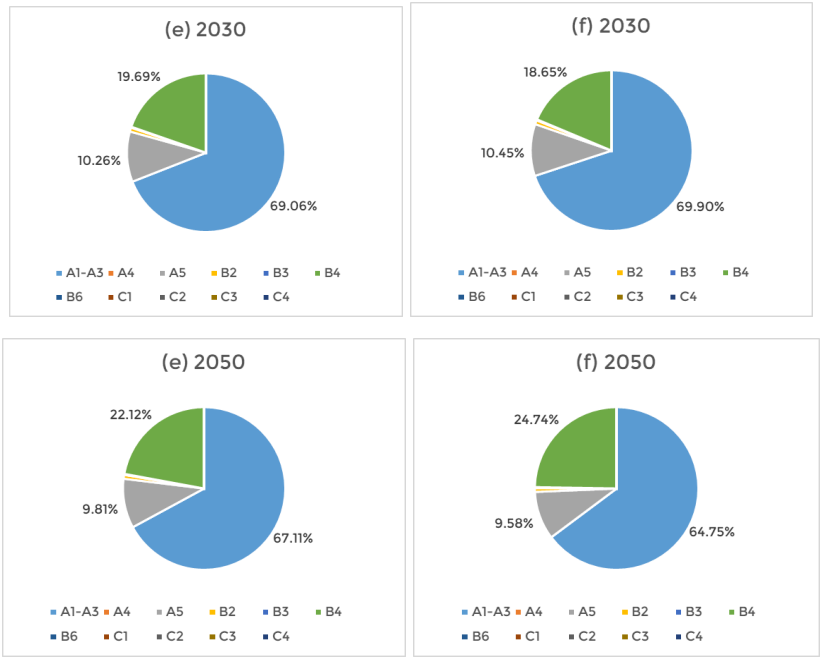


Figure 39: Absolute improvement (%) by LCM for OFF (e), (f) for 2030, 2050

For the OFF typologies, Figures 35–39 indicate a trend consistent with that observed for the residential typologies, although with some differences in the relative contribution of the individual modules. In 2030, the reduction in module A1-A3 is approximately 18–22%, while B4 is reduced by 6–10% and B2-B3 by 17–20%, with an overall WLC GWP reduction ranging from 8% to 12%.

In 2050, the higher diffusion levels assumed for the measure lead to larger reductions: A1-A3 is reduced by 49–56%, B4 by 24–31% and B2-B3 by 44–51%. The overall WLC GWP reduction reaches 24–31%.

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Assessment results for WLC measure 5.3: Carbon capture, utilisation and storage in production

The results for WLC measure 5.3 assess the application of carbon capture, utilisation and storage technology to cement production in the representative Italian case study. Figures 40 and 41 report the assessment results: Figure 40 compares the baseline scenario with the scenario including CEM-CCS, with GWPtot impacts broken down by LCM, while Figure 41 shows the contribution of each module to the absolute improvement.

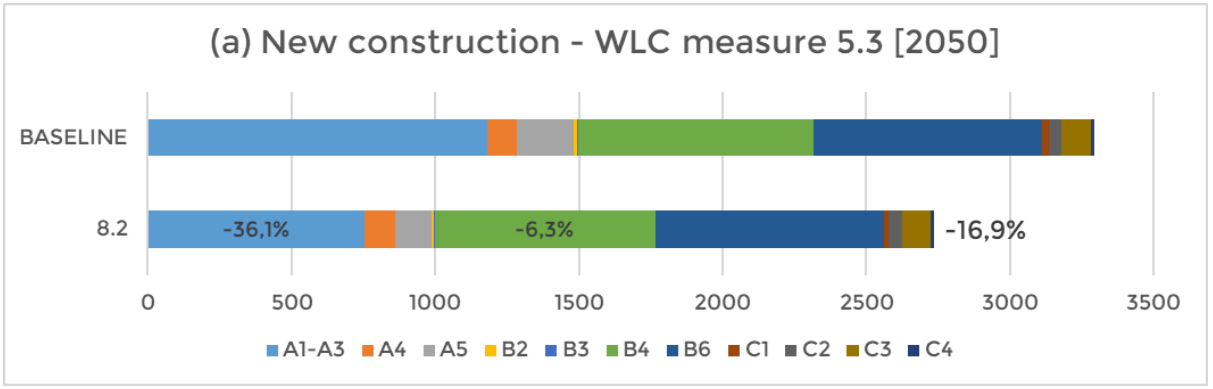


Figure 40: Comparison between the baseline and the new results for WLC measure 5.3 to 2050 of the MFH case study (a). GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

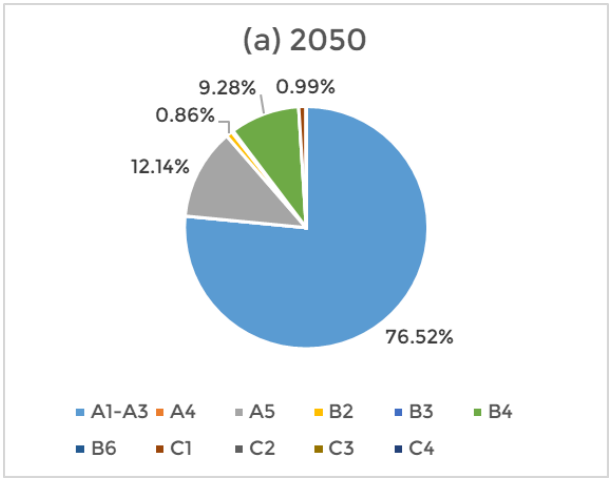


Figure 41: Absolute improvement (%) by LCM

The results reported in Figures 40 and 41 show the potential benefits of applying CEM-CCS to the representative Italian case study IT_MFH_01_N_E_3. GWP reductions are mainly concentrated in module A1-A3, where the impact is reduced by 36.1%. This is consistent with the scope of the measure, which acts directly on the cement production process. A smaller reduction is also observed in module B4, equal to 6.3%, reflecting the indirect effect of using lower-carbon cement in replacement-related processes. Figure 41 further confirms that A1-A3 accounts for the largest share of the absolute improvement, while B4 provides a secondary contribution and the remaining modules contribute only marginally.

Other modules, including A5, B2 and C1, are also affected, although only to a limited extent. These variations are mainly linked to the assumptions adopted by the Italian

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consortium in the WLC modelling framework and should therefore not be interpreted as direct effects of the measure.

Overall, the results show that the application of CCS technology to cement production can contribute to reducing CO_2 emissions from the building sector. However, to achieve a more systematic and significant decarbonisation effect, the measure should be extended to other high-impact production processes, such as steel and glass, and combined with additional measures. It will also be important to assess the effectiveness of the CO_2 storage system in order to avoid shifting emission-related burdens to other stages or actors.

6.2.3. Strategy 6 results: Reduce emissions from transport of materials and construction products

This section presents the assessment results for Strategy 6, which focuses on reducing emissions associated with the transport of construction materials and products to the building site. The analysis includes two WLC measures: 6.1, based on local sourcing to reduce transport distances, and 6.2, based on the use of low-carbon transportation alternatives.

Assessment results for WLC measure 6.1: reducing the distance materials travel to construction sites by favouring local sourcing

Figures 42 and 43 report the results for WLC measure 6.1. Figure 42 compares the baseline scenario with the local sourcing scenario, while Figure 43 shows the contribution of each LCM to the absolute improvement.

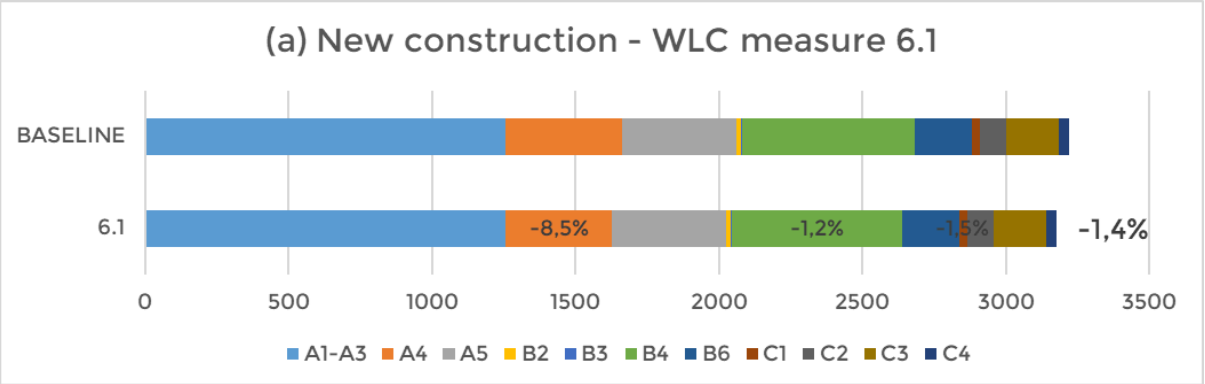


Figure 42: Comparison between the baseline and the new results for WLC measure 6.1. GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

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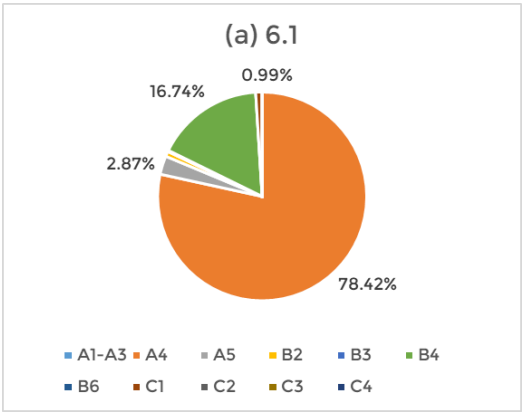


Figure 43: Absolute improvement (%) by LCM

As shown in Figures 42 and 43, WLC measure 6.1 results in an overall WLC GWP reduction of 1.4%, mainly driven by module A4, where impacts are reduced by 8.5%. This module accounts for approximately 78% of the total GWP benefit, confirming that the main effect of the measure is associated with transport-related impacts. A secondary contribution is observed in module B4, with a reduction of 1.2%, corresponding to approximately 16% of the total benefit, while a minor reduction is recorded in module C1, equal to 1.5%.

Assessment results for WLC measure 6.2: employing low-carbon transportation alternatives

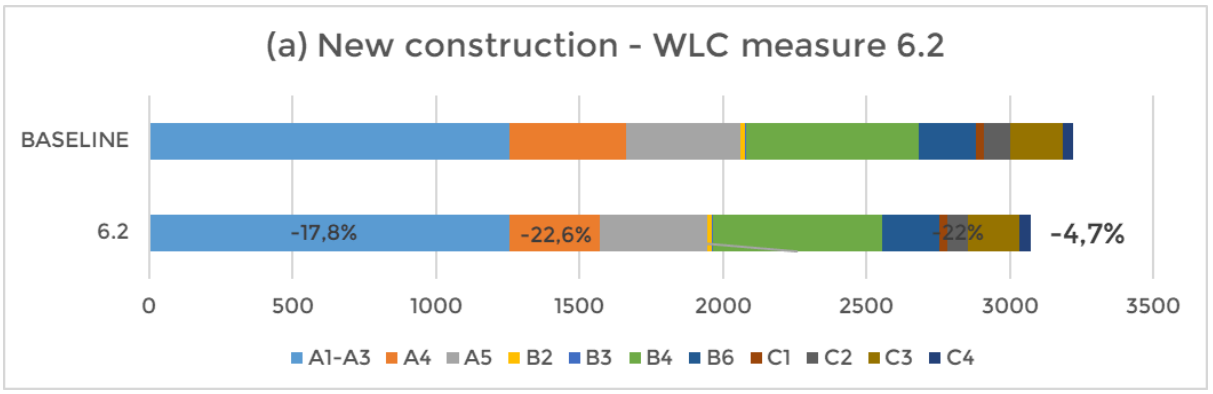


Figure 44: Comparison between the baseline and the new results for WLC measure 6.2. GWPtot impacts are divided by LCMs. Climate zone E, seismic zone 2

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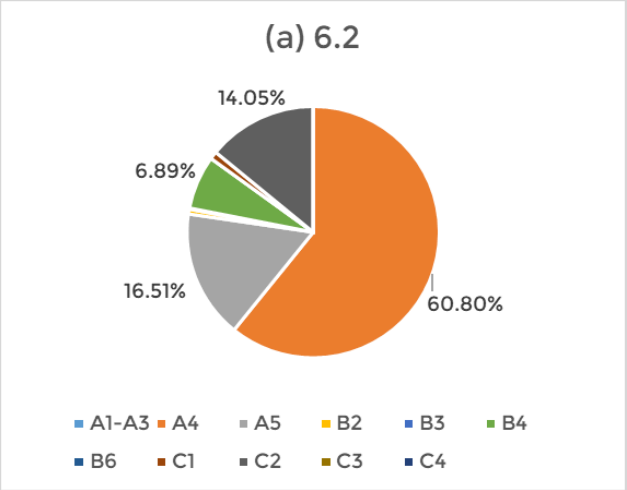


Figure 45: Absolute improvement (%) by LCM

As shown in Figures 44 and 45, WLC measure 6.2 results in an overall WLC GWP reduction of 4.7%. Figure 44 compares the baseline scenario with the scenario resulting from the application of low-carbon transportation alternatives, with GWPtot impacts broken down by LCM. Figure 45 reports the contribution of each LCM to the absolute improvement.

The reduction is mainly driven by module A4, where impacts decrease by 22.6%. This module accounts for 60.8% of the total GWP benefit, confirming that the main effect of the measure is associated with the adoption of low-carbon transportation alternatives for construction materials and products. Additional relevant contributions are observed in module A5, with a reduction of 6.2%, corresponding to 16.5% of the total benefit, and in module C2, where impacts decrease by approximately 22%, representing 14.0% of the total benefit. Module B4 also contributes to the overall reduction, with a decrease of 1.7%, corresponding to 6.9% of the total benefit.

Minor reductions are also observed in modules B2/B3 and C1. However, these are not considered direct effects of WLC measure 6.2. In particular, C1 refers to deconstruction/demolition activities and is therefore not directly related to transport-related decarbonisation. These reductions are linked to the calculation assumptions adopted in the WLC assessment framework, as described in D7.20, and will be excluded in the following chapter from the benefits directly attributable to this measure.

6.2.4. Strategy 8 results: Increase circular material use

This section presents the assessment results for the WLC measure analysed under **Strategy 8**, with a focus on increasing the use of materials with high recycled content. The measure acts mainly on the carbon intensity of material production and therefore primarily affects module **A1-A3**, while additional effects may be observed in modules linked to maintenance, repair and replacement processes.

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Assessment results for WLC measure 8.2: use of materials with high recycled content

For WLC measure 8.2, the results are reported for the assessed **SFH, MFH and OFF** typologies. For each typology, the figures compare the baseline scenario with the scenario resulting from the use of materials with higher recycled content, with GWPtot impacts broken down by LCM. The final figure for each typology reports the contribution of each module to the absolute improvement.

For the SFH typologies, Figures 46–48 report the results for two case studies, labelled as SFH case study (a) and SFH case study (b).

SFH

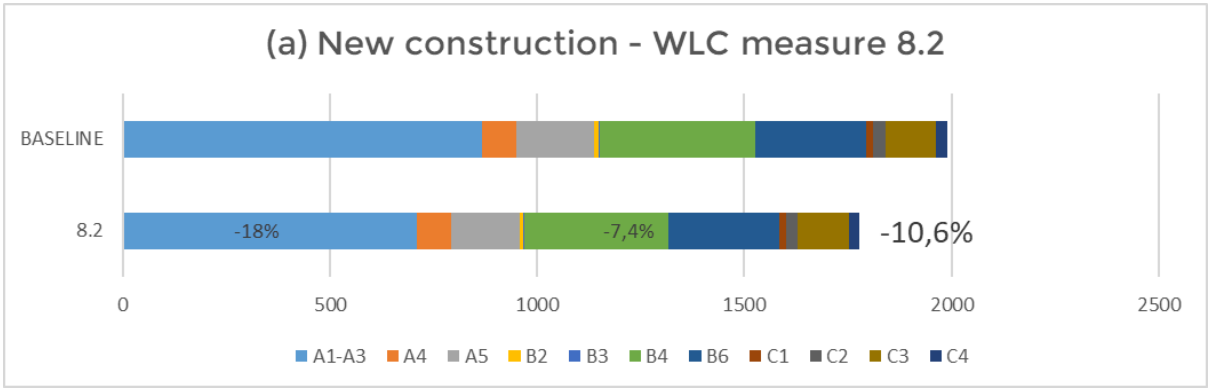


Figure 46: Comparison between the baseline and the new results for WLC Measure 8.2 of SFH case study (a). GWPtot impacts divided by LCMs. Climate zone E, seismic zone 2

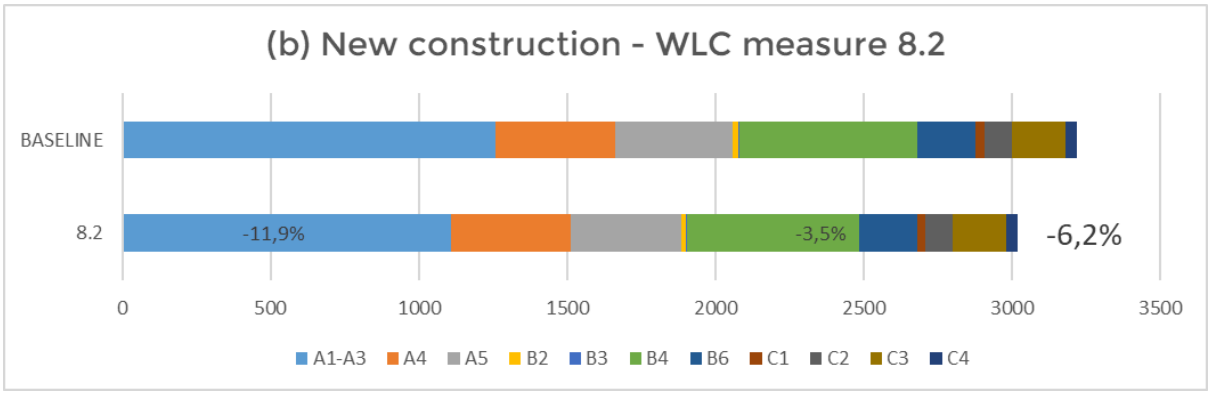


Figure 47: Comparison between the baseline and the new results for WLC Measure 8.2 of SFH case study (b). Emissions per LCM (normalized by HFA). Climate zone E, seismic zone 2

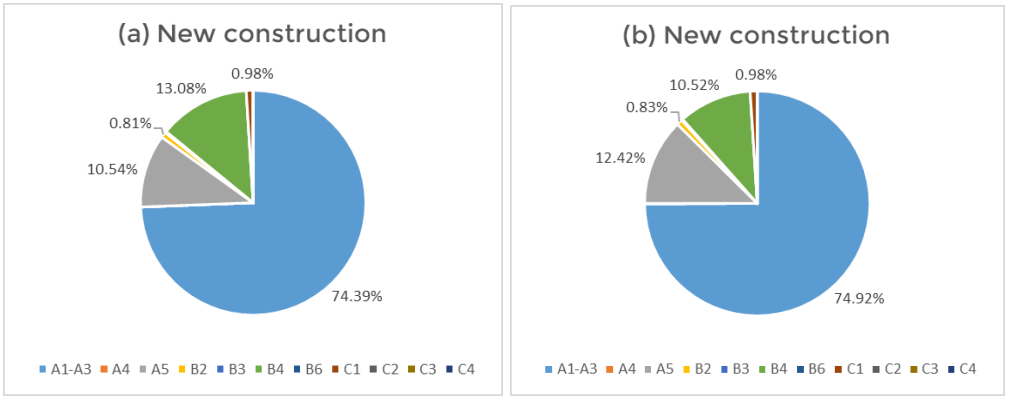


Figure 48: Absolute improvement (%) by LCM for SFH (a), (b)

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Figures 46 and 47 compare the baseline scenario with the scenario resulting from the use of materials with higher recycled content, while Figure 48 shows the contribution of each LCM to the absolute improvement for both cases.

The application of WLC measure 8.2 results in an overall WLC GWP reduction ranging from 6.2% in case study (b) to 10.6% in case study (a). In both cases, the reduction is mainly driven by module A1-A3, where impacts decrease by 11.9% in case study (b) and by 18.0% in case study (a). This confirms that the measure primarily affects production-stage emissions.

Module B4 shows a more limited reduction, equal to 3.5% in case study (b) and 7.4% in case study (a). Modules B2 and B3 also decrease, consistently with their dependency on the carbon intensity of materials. As shown in Figure 48, A1-A3 accounts for the largest share of the absolute improvement in both SFH cases, approximately 74–75%, followed by B4 and A5. Modules A4, B6, C2, C3 and C4 remain unchanged, as they are not affected by the variation in the production dataset.

For the MFH typologies, **Figures 49–51** report the results for two case studies, labelled as MFH case study (c) and MFH case study (d). Figures 49 and 50 compare the baseline scenario with the scenario resulting from the use of materials with higher recycled content, while Figure 51 shows the contribution of each LCM to the absolute improvement for both cases.

MFH

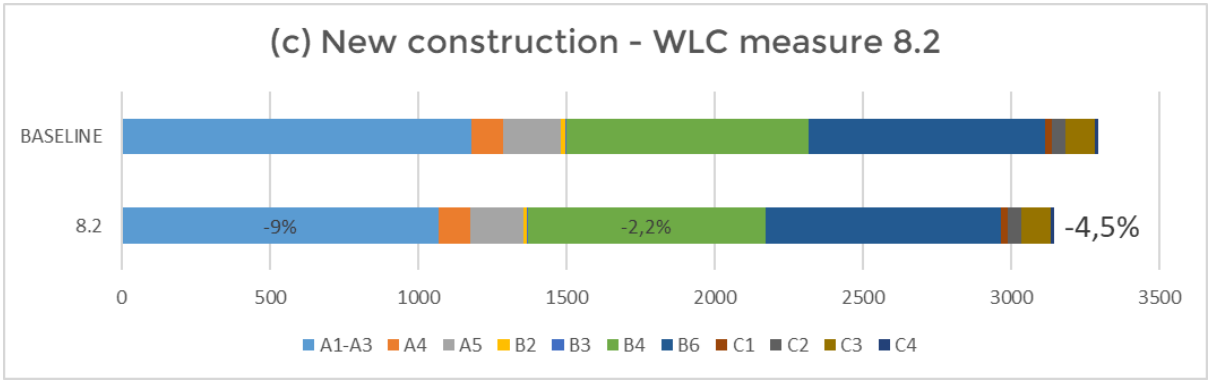


Figure 49: Comparison between the baseline and the new results for WLC Measure 8.2 of MFH case study (c). GWPtot impacts divided by LCMs. Climate zone E, seismic zone 2

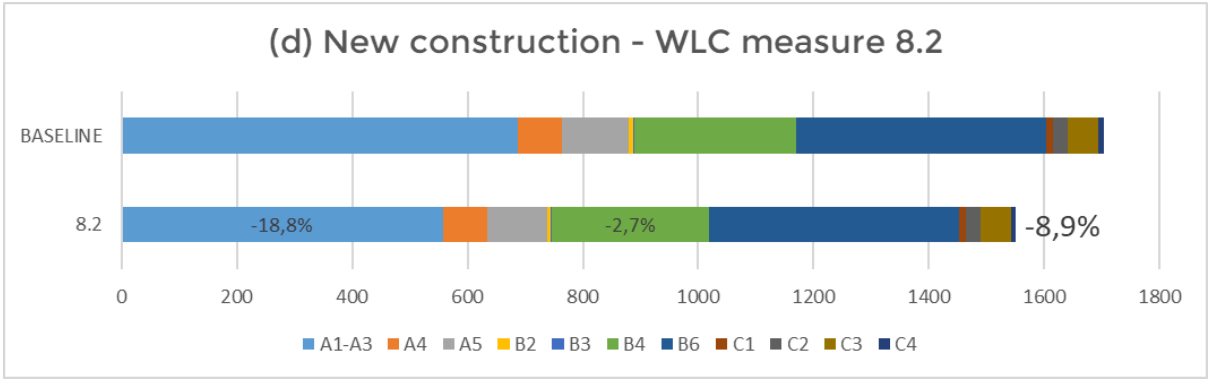


Figure 50: Comparison between the baseline and the new results for WLC Measure 8.2 of MFH case study (d). GWPtot impacts divided by LCMs. Climate zone E, seismic zone 2

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The application of WLC measure 8.2 results in an overall WLC GWP reduction ranging from 4.5% in case study (c) to 8.9% in case study (d). In both cases, the reduction is mainly driven by module A1-A3, where impacts decrease by 9.0% in case study (c) and by 18.8% in case study (d). This confirms that the measure primarily affects production-stage emissions, although with a more pronounced difference between the two MFH cases compared with the SFH typologies.

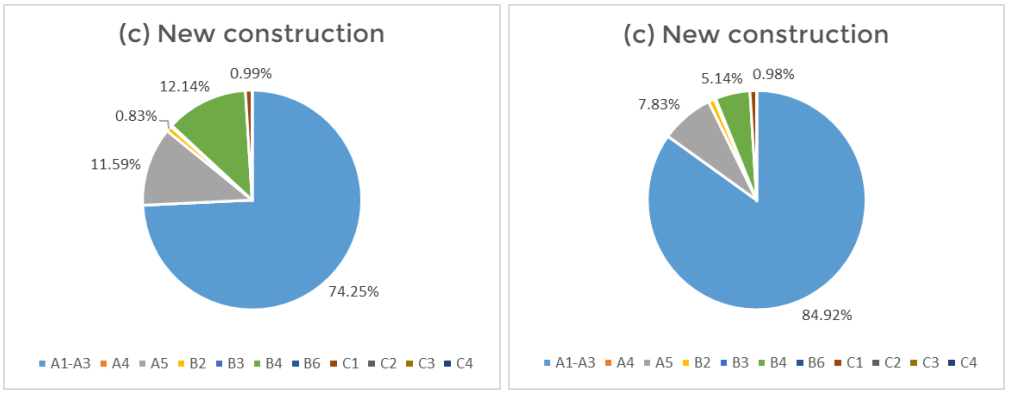


Figure 51: Absolute improvement (%) by LCM for MFH (c), (d)

Module B4 shows a more limited reduction, equal to 2.2% in case study (c) and 2.7% in case study (d). Modules B2 and B3 also decrease, consistently with their dependency on the carbon intensity of materials. As shown in Figure 51, A1-A3 accounts for the largest share of the absolute improvement in both MFH cases, although its contribution is higher in case study (d). This suggests a greater variability in material composition within the MFH typology. Modules whose results are independent of material carbon intensity remain unchanged.

For the OFF typologies, **Figures 52–54** report the results for two case studies, labelled as OFF case study (e) and OFF case study (f). Figures 52 and 53 compare the baseline scenario with the scenario resulting from the use of materials with higher recycled content, while Figure 54 shows the contribution of each LCM to the absolute improvement for both cases.

OFF

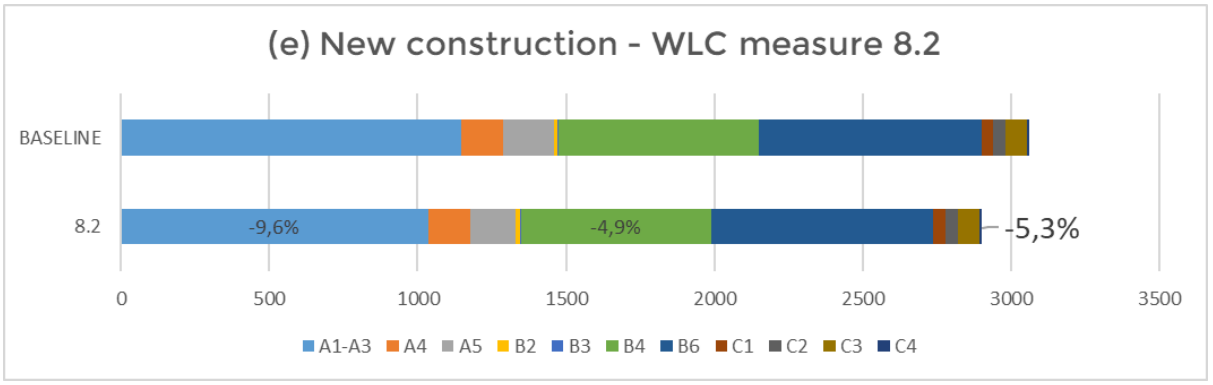


Figure 52: Comparison between the baseline and the new results for WLC Measure 8.2 of OFF case study (e). GWPtot impacts divided by LCMs. Climate zone E, seismic zone 3

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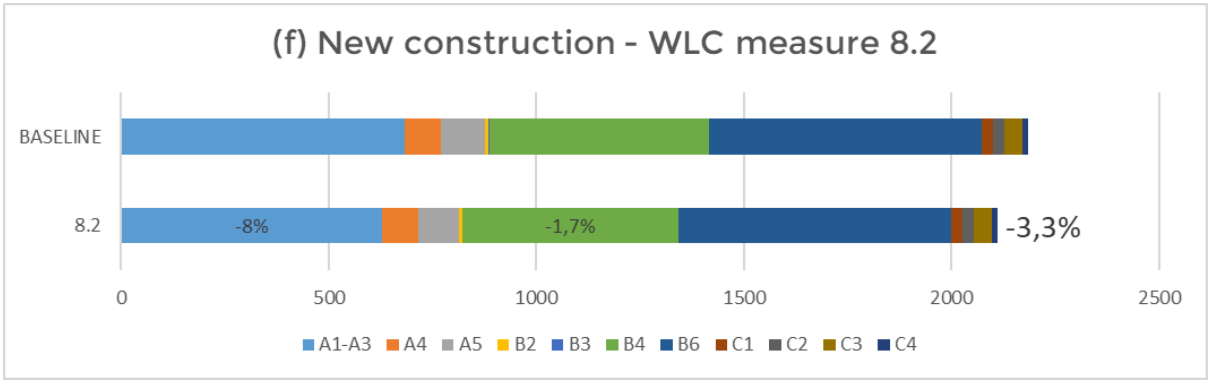


Figure 53: Comparison between the baseline and the new results for WLC Measure 8.2 of OFF case study (f). GWPtot impacts divided by LCMs. Climate zone E, seismic zone 3

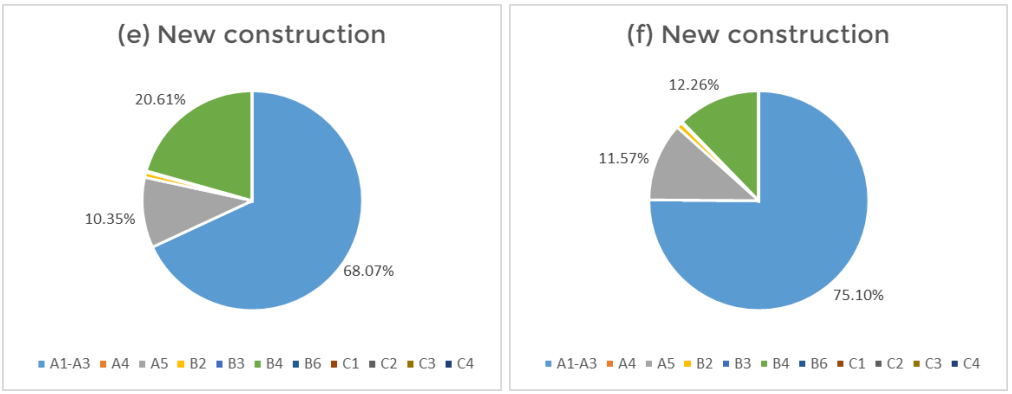


Figure 54: Absolute improvement (%) by LCM for OFF (e), (f)

The application of WLC measure 8.2 results in an overall WLC GWP reduction ranging from 3.3% in case study (f) to 5.3% in case study (e). In both cases, the reduction is mainly driven by module A1-A3, where impacts decrease by 8.0% in case study (f) and by 9.6% in case study (e). This confirms that the measure primarily affects production-stage emissions, although the overall reduction is lower than that observed for the residential typologies.

Module B4 shows a more limited reduction, equal to 1.7% in case study (f) and 4.9% in case study (e). Modules B2 and B3 also decrease, consistently with their dependency on the carbon intensity of materials. As shown in Figure 54, A1-A3 accounts for the largest share of the absolute improvement in both OFF cases, ranging from 68.07% in case study (e) to 75.10% in case study (f). Modules whose results are independent of material carbon intensity remain unchanged.

6.2.5. Strategy 9 results: Reduce operational carbon emissions

This section presents the assessment results for the WLC measures analysed under Strategy 9, which focuses on the reduction of operational carbon (OC) emissions. The analysis considers WLC measure 9.5, aimed at increasing the renewable share of the energy mix and reducing the carbon intensity of operational energy use, with specific reference to module B6.

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Assessment results for WLC measure 9.5: increase renewable energy

Results are expressed as the EC/OC percentage share in order to assess how the reduction of emissions associated with module **B6** modifies the relative weight of OC across the building typologies analysed. This allows the effect of the measure to be interpreted not only in terms of B6 reduction, but also in relation to the overall structure of the whole life carbon balance.

As shown in **Figure 55**, WLC measure 9.5 produces a reduction in the relative share of **OC** across all building typologies analysed. The OC share decreases from **15% to 12%** for **SFH**, from **27% to 21%** for **MFH+HOS**, from **56% to 49%** for **OFF**, and from **11% to 8%** for **XTR/EDU**. As a consequence, the relative share of **EC** increases in all typologies, reflecting the lower contribution of operational emissions after the application of the measure.

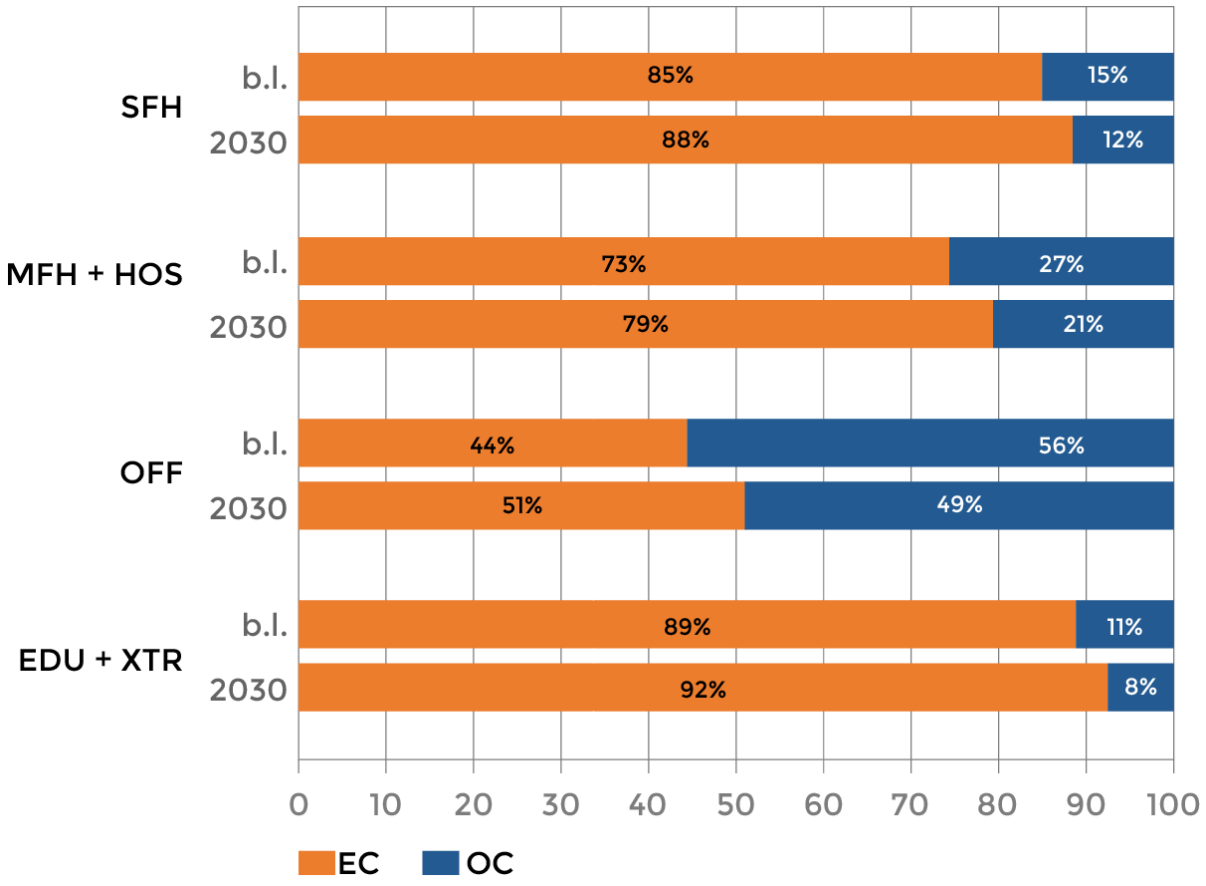


Figure 55: Results expressed as EC/OC percentage shares by building typology, baseline and 2030 scenario

The largest absolute variation is observed in the **OFF** typology, where the OC share decreases by **7 percentage points**, from **56% to 49%**. This is the only typology in which the baseline condition is characterised by a prevalence of OC over EC. After the application of the measure, the balance shifts to a slightly EC-dominant condition. This is confirmed by the **OC/EC ratio**, which decreases from **127.3** to **96.1**.

For **MFH+HOS**, the OC share decreases by **6 percentage points**, from **27% to 21%**, with the OC/EC ratio moving from **37.0** to **26.6**. For **SFH** and **XTR/EDU**, the absolute reduction amounts to **3 percentage points**. In these cases, the OC/EC ratio decreases from **17.6** to **13.6** for SFH and from **12.4** to **8.7** for XTR/EDU.

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Overall, the results indicate that WLC measure 9.5 reduces the operational component across all assessed typologies. The effect is more evident where OC has a higher initial weight, as observed for **OFF** and, to a lesser extent, **MFH+HOS**. In typologies already dominated by EC, such as **SFH** and **XTR/EDU**, the measure reduces OC but does not substantially modify the overall carbon balance.

6.2.6. Strategy 11 results: Use of carbon dioxide removal (CDR) solutions

This section presents the assessment results for the WLC measures analysed under Strategy 11, which focuses on the use of carbon dioxide removal solutions in the built environment. The analysis considers WLC measure 11.1, related to the integration of green roofs and/or green façades.

Assessment results for WLC measure 11.1: green roofs and/or green façades

In the remodelling scenario, module B1 is introduced as an additional life-cycle contribution, whereas it is not present in the baseline scenario.

It is also important to note that the reference standards -EN 15804 and EN 15978- do not clearly define in which LCM the benefits associated with greenery should be reported. Therefore, the allocation of this benefit to module B1 is a methodological assumption adopted for the purposes of this assessment.

For the purpose of comparability, B1 is assumed to be equal to zero in the baseline **scenario** and is reported explicitly in the remodelling scenario. Since B1 represents a negative contribution, the WLC result is calculated as the algebraic sum of all positive and negative module contributions.

To avoid misinterpretation, the positive **contributions of the different** LCMs are reported **cumulatively**, while B1 is shown separately as a negative contribution.

The net WLC value of each scenario is then reported as the final algebraic total. Accordingly, **B1** is not interpreted as a percentage reduction relative to the baseline module value, but as an additional contribution to the overall WLC reduction achieved by the remodelling scenario.

As shown in Figure 56, the inclusion of module B1 in the remodelling scenario results in an overall GWPtot reduction of approximately 3% for the assessed case study. This reduction is linked to the additional negative contribution associated with CO_2 absorption from the green roof, rather than to a reduction of a corresponding baseline module.

As reported in chapter 5, to quantify the B1 carbon absorption the value of −1.232 $kgCO_2/m^2/year$ was selected as the reference absorption rate for an intensive green roof, multiplied by the roof area (813 m^2) and the reference study period (50 years), yielding a total B1 module input value of −50,080.8 $kgCO_2$ for the WLC model.

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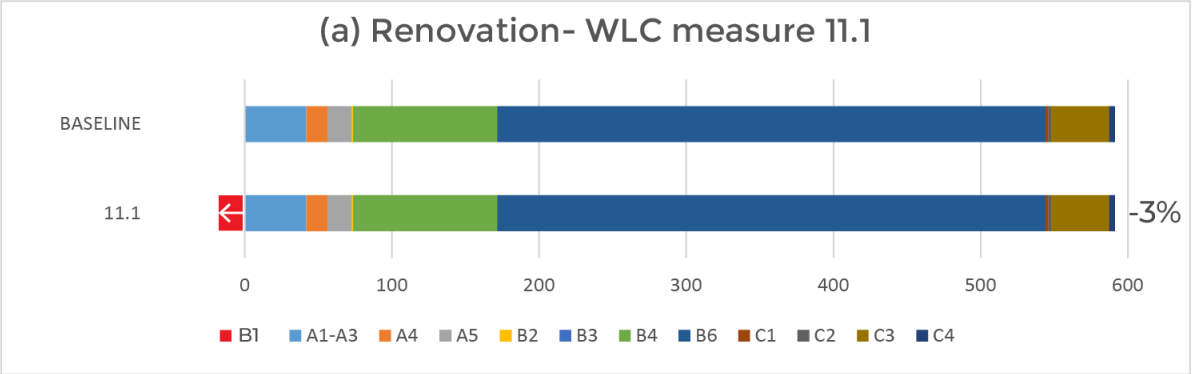


Figure 56: Influence of the CO2 absorption from green roof applied to the case study IT_MFH_11_R_E_3

The results indicate that the integration of greenery can contribute to reducing the overall WLC balance when designed and implemented according to appropriate technical guidance, such as UNI 11235:2015. In addition to the carbon-related benefit assessed through LCA, green roofs and green façades may provide further benefits that are not fully captured by the WLC assessment, including stormwater management, improved thermal regulation, mitigation of the urban heat island effect and increased well-being of occupants. However, further assessment is needed to better understand the impacts associated with additional maintenance operations required by green infrastructure, as also highlighted by Nordic Innovation (2024).

In the assessed case study, which concerns a renovation intervention, the adopted technology is relevant because it consists of a lightweight system applied to the existing building without requiring structural improvement. As an easy-to-assemble system, it can contribute to minimising EC values in modules A1-A3 and A5.

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7. Target definition

The preceding chapters have systematically analysed a set of WLC reduction strategies, quantifying (through modelling applied to representative case studies of the Italian building stock) the improvements at building and LCMs level. The processing and integrated interpretation of these results were carried out by UNIBG to support target definition. The values are normalised in terms of GWP/HFA, in order to allow comparison across different building typologies and to express the reduction potential in a consistent functional metric. Where sufficient evidence is available, target values are differentiated by building typology, distinguishing between SFH, MFH+HOS, and OFF typology groups.

The proposed target values are derived from the comparison between the baseline scenario and the remodelled scenarios associated with the selected WLC measures. Particular attention in this chapter is given to distinguishing **effective reductions** directly attributable to the decarbonisation strategies from reductions resulting from methodological assumptions already embedded in the baseline or in the modelling framework. This distinction is necessary to avoid overestimating the contribution of individual measures and to ensure that the target values reflect the actual reduction potential of the strategies under investigation.

The target values should be understood as an indicative extension of the baseline benchmarks developed in the previous phases of the INDICATE LIFE IT project. They do not represent regulatory thresholds, but rather evidence-based reference values describing the WLC performance levels that may be achieved when selected decarbonisation measures are implemented individually or in combination. In this sense, they provide a methodological link between WLC reduction strategies and measurable building-level performance outcomes.

Section 7.1 revisits the results of the individual WLC measures, providing a refinement and interpretation of the findings (Box A in Figure 57). Section 7.2 interprets the results according to two analytical perspectives: the first organises the findings by aggregated LCM groups (A1–A3, A4–A5, B1–B6 and C1–C4), while the second aggregates them according to the reference pathways of the ASI framework. Section 7.3 then performs a final remodelling of selected case studies by applying the maximum combination of the assessed strategies.

Figure 57 outlines the analytical sequence followed in this chapter.

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Figure 57. Analytical sequence of Chapter 7

7.1. WLC strategies target definition

This section presents the target values derived for each WLC measure assessed quantitatively. Building upon the results presented in the previous chapter, the **achievable reductions** associated with **each measure** are analysed in order to define representative **target values** for the different building typologies considered.

The interpretation of the results follows the analytical framework described below.

7.1.1. Analytical framework for the interpretation of results

To ensure consistency in the interpretation of the quantitative results, a common analytical format is adopted in this chapter. While **Chapter 6** presents the numerical outcomes of the remodelling activities and compares them with the baseline scenario, the present chapter provides a critical reading of those results, explaining the main trends observed and clarifying the mechanisms through which each WLC measure affects the overall WLC balance.

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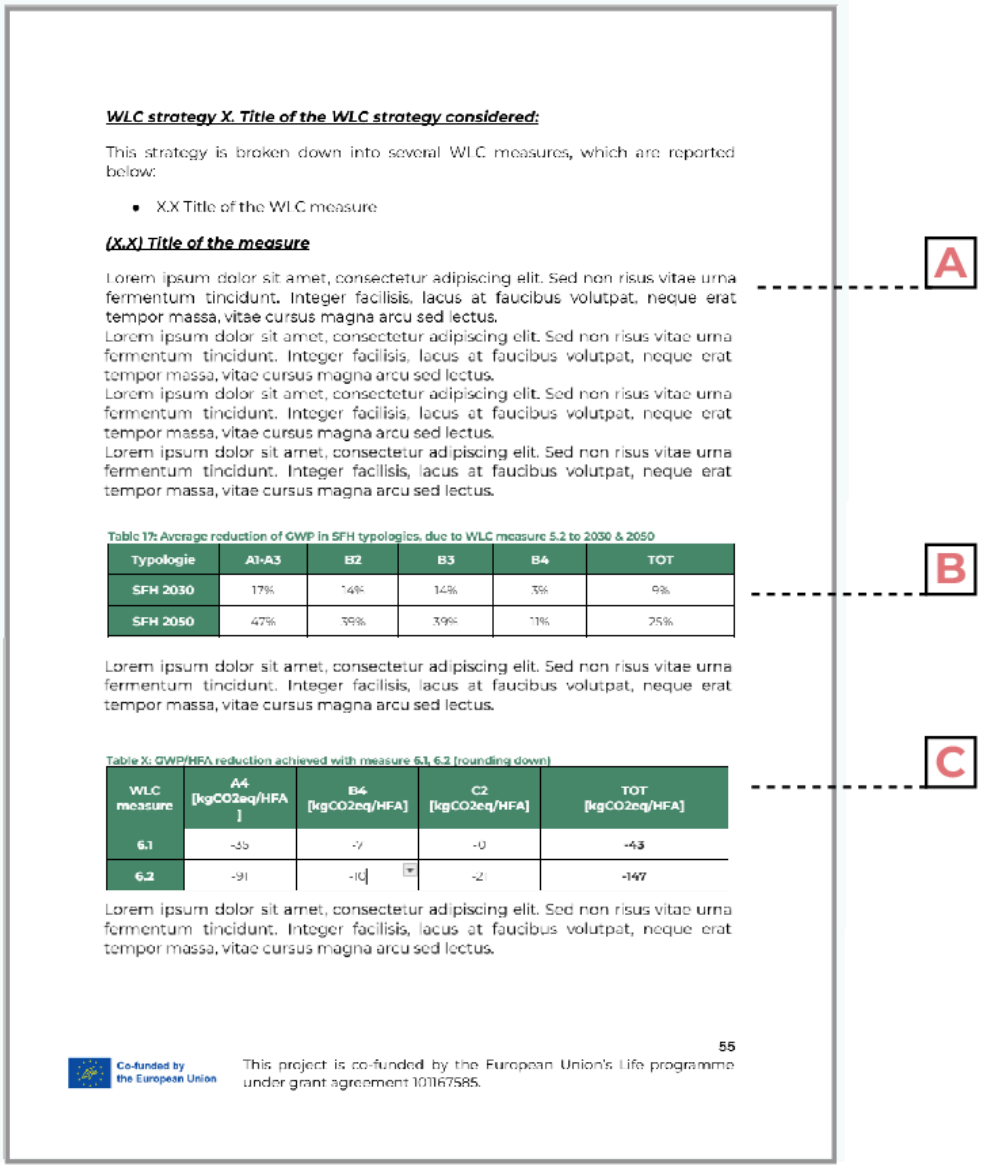
Each WLC measure assessed through the quantitative approach is analysed in relation to the results previously reported. The objective is both to describe the magnitude of the reduction achieved and to interpret how this reduction is distributed across LCMs.

Where supported by the **available level of detail**, the analysis is differentiated by building typology and/or by reference year of the modelling scenario. This distinction is particularly relevant for measures whose effects vary according to the characteristics of the analysed building groups, such as SFH, MFH+HOS and OFF, or according to the temporal assumptions adopted for future scenarios, such as the 2030 and 2050 horizons. In this way, the analysis allows both typology-specific responses and time-dependent decarbonisation trajectories to be identified.

For each measure, the discussion first provides a critical overview of the results, highlighting the main variations compared with the baseline, the LCMs most affected, and the methodological aspects that influence the interpretation of the outcome (**Box A** in **Figure 58**). This qualitative reading is then supported by a **summary table** reporting the average **GWP reduction** by **LCM**, expressed as a percentage variation relative to the baseline (**Box B** in Figure 58). The purpose of this table is to show, for each affected module, the extent to which impacts decrease as a result of the measure. In this table, grey-highlighted cells identify improvements that result from modelling assumptions adopted within the Italian consortium, rather than from the direct effect of the decarbonisation strategy itself. This distinction is introduced to avoid attributing to the WLC measure reductions that are instead generated by the calculation approach or by assumptions embedded in the reference dataset. Finally, a second summary table reports the normalised reductions in terms of GWP/HFA (**Box C** in Figure 58). This table provides an overall view of the effective improvements achieved by each measure, expressed through a common functional metric and therefore suitable for comparison across measures and building typologies. Only **effective reductions** directly attributable to the measure are included in this final table, while improvements previously identified as assumption-driven are excluded from the effective reduction calculation and identified accordingly in the table. This approach supports a more robust interpretation of the results and provides the basis for the subsequent definition of indicative WLC target values.

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WLC strategy X. Title of the WLC strategy considered:

This strategy is broken down into several WLC measures, which are reported below:

- X.X Title of the WLC measure

(X.X) Title of the measure

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A

Table 17: Average reduction of GWP in SFH typologies, due to WLC measure 5.2 to 2030 & 2050

Typologie	A1-A3	B2	B3	B4	TOT
SFH 2030	17%	14%	14%	3%	9%
SFH 2050	47%	39%	39%	11%	25%

B

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Table X: GWP/HFA reduction achieved with measure 6.1, 6.2 (rounding down)

WLC measure	A4 [kgCO2eq/HFA]	B4 [kgCO2eq/HFA]	C2 [kgCO2eq/HFA]	TOT [kgCO2eq/HFA]
6.1	-35	-7	-0	-43
6.2	-91	-10	-2	-147

C

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Figure 58: Reporting format adopted for the results of WLC measures assessed quantitatively

To improve the transparency and traceability of the target definition process, the reference case study is summarised in **Table 16**, together with the corresponding **baseline WLC-GWP value**. The baseline represents the WLC-GWP value before the application of the selected decarbonisation measure and is used as the reference against which both absolute and percentage reductions are calculated. Baseline values are reported respectively in **kgCO₂eq/GFA** and **kgCO₂eq/HFA**.

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Table 16. Reference case studies, typologies and baseline WLC-GWP values used for target definition

WLC measure	Reference typology	Case study	Baseline value	
			GWP/GFA [$kgCO_2eq/m^2$]	GWP/HFA [$kgCO_2eq/m^2$]
2.4.a	(MFH)*	MFH_18	1135.5	1795.3
2.4.b				
5.2	SFH	SFH_09	883.9	1990
		SFH_10	969.3	3221.7
	MFH	MFH_01	1541.4	3293
		MFH_14	784	1702.5
	OFF	OFF_11	1534.4	3063.3
		OFF_13	1366.5	2183.1
5.3	(MFH)*	MFH_01	1541.4	3293
6.1	(SFH)*	SFH_10	969.3	3221.7
6.2	(SFH)*	SFH_10	969.3	3221.7
8.2	SFH	SFH_09	883.9	1990
		SFH_10	969.3	3221.7
	MFH	MFH_01	1541.4	3293
		MFH_14	784	1702.5
	OFF	OFF_11	1534.4	3063.3
		OFF_13	1366.5	2183.1
9.5	Modellation performed for all New Construction case studies			
11.1	(MFH)*	MFH_11	339.7	591.2

*Measure assessed on a single representative case study or building typology, with the result used as a reference for all categories considered in the report.

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7.1.2. Strategy 2 target definition: Prioritise better use, renovation and repair over demolition and new construction

Target definition for WLC measure 2.4: Design for durability and maintainability of building components

In this analysis the authors introduced WLC Measure 2.4 as an **additional measure**, whose first modelling approach (2.4.a) explores the benefit of a more granular characterisation of composite building assemblies, considering sub-components with significantly different service lives rather than applying a single replacement interval to the assembly as a whole. This distinction carries both a methodological and a design implication. On the methodological side, the Level(s) framework assigns replacement intervals at the category level (a convention that, while practical for benchmark assessments, conflates elements whose technical durability differs substantially). On the design side, the measure proposes that components whose service life exceeds the RSP, but which may nonetheless be disturbed by architectural modifications during the building's life, are not at end-of-life when the intervention occurs: they retain their functional and structural integrity and can therefore be reused within the same building rather than replaced with new material.

In the case study examined, this logic is applied to the metal substructure of the drywall partition system. Under normal indoor conditions, steel profiles embedded in a dry partition do not degrade within a 50-year RSP; when a partition is relocated or reconfigured, the substructure can be dismantled and reinstalled without loss of performance. Modelling this reuse (and attributing the B4 contribution solely to the gypsum board layer, which is genuinely replaced) yields a 14% reduction in module B4 and **an overall WLC reduction of 4.4%**. The result quantifies the combined effect of increased modelling resolution and a reuse-oriented approach to components that retain residual service life at the time of intervention. The same logic is in principle applicable to other assemblies in the dataset where structurally durable sub-components are grouped with shorter-lived finishing layers under a single replacement assumption, suggesting that the potential of this approach extends beyond the single case study presented here.

The reduction of the individual LCMs compared with the baseline is reported in Table 17. The values highlighted in grey indicate the improvements resulting from the assumptions adopted by the Italian consortium and described in **D7.20**, which are therefore not directly attributable to the decarbonisation strategy itself.

Table 17: Average reduction of GWP due to WLC measure 2.4.a (on MFH)

Typology	B2	B4	C1	TOT
(MFH)	0%	14%	6,5%	**4,4%**

The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation. For **Measure 2.4.b**, the **overall WLC reduction of 1.2%** recorded should not be interpreted as a limitation of the maintenance approach as such, but rather as an inherent feature of the trade-off it introduces: replacing a full substitution cycle with a lighter maintenance intervention reduces B4 but

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simultaneously generates a new B2 contribution, and the net benefit reflects the balance between these two effects. The result confirms that a maintenance-oriented strategy does not unconditionally reduce total embodied impacts (it shifts them across modules) and that the overall lifecycle balance is the correct metric against which to evaluate the measure, rather than the performance of any single module in isolation.

It is equally important to contextualise the magnitude of the improvement. The 1.2% refers exclusively to the maintenance of the interior paint layer, which represents one sub-component within the broader Tier 2.1 assembly. The same logic (substituting periodic partial interventions for full material replacement) is in principle applicable to other finishing elements where technically feasible. Were the maintenance approach extended systematically across all eligible components, the cumulative B4 reduction and corresponding net WLC benefit would be substantially larger. The result obtained here should therefore be understood as a lower-bound estimate of the potential of Measure 2.4.b, scoped to a single material for demonstrative purposes, and not as a comprehensive assessment of the strategy's decarbonisation potential.

Table 18: Average reduction of GWP due to WLC measure 2.4.b (on MFH)

Typology	B2	B4	C1	TOT
(MFH)	+31,7%	4,1%	1,6%	**1,1%**

The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation.

The reductions reported in Table 19 are expressed in terms of GWP/HFA for the individual LCMs relative to the baseline. Only **effective reductions** are shown. Reductions resulting solely from modelling assumptions are not retained from the effective reduction calculation and marked as "**NR**" in the table.

Table 19: Average GWP/HFA reduction achieved with measure 2.4.a, 2.4.b, rounding down

Measure	B2 [kgCO2eq/HFA]	B4 [kgCO2eq/HFA]	C1	TOT [kgCO2eq/HFA]
2.4.a	0	-78	NR	**-78**
2.4.b	+3	-23	NR	**-20**

To convert the absolute reductions reported in Table 19 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,6325**. Percentage reductions shown in Table 18 are not affected by this conversion.

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7.1.3. Strategy 5 target definition: Reduce emissions from traditionally high impact construction materials

Target definition for WLC measure 5.2: Renewable energy sources in production

The target definition for WLC measure 5.2 is based on the average reductions obtained for the assessed building typologies at the 2030 and 2050 horizons. Since the measure acts on the energy sources used in the production processes of high-impact construction materials, the primary target is associated with the reduction of production-stage impacts, represented by module A1-A3.

The following tables report the average reduction values by typology and LCM. These values are used to define the expected target range for each building typology and to compare the response across typologies.

SFH typologies - 2030 & 2050

For SFH typologies, as reported in **Table 20** , the target is mainly driven by the reduction of module A1-A3, which decreases by **17% at 2030** and **47% at 2050**. This corresponds to an average overall WLC GWP reduction of **9% in 2030** and **25% in 2050**. The contribution of B4 remains more limited, while B2 and B3 follow the reduction trend of A1-A3 according to the modelling assumptions adopted in the assessment.

Table 20: Average reduction of GWP in SFH typologies, due to WLC measure 5.2 to 2030 & 2050

Typology	A1-A3	B2	B3	B4	TOT
SFH 2030	17%	14%	14%	3%	**9%**
SFH 2050	47%	39%	39%	11%	**25%**

MFH typologies - 2030 & 2050

For MFH typologies, the target values are consistent with those observed for SFH. As reported in Table 21, the reduction of module A1-A3 is 18% at 2030 and 49% at 2050, leading to an average overall WLC GWP reduction of 9% at 2030 and 24% at 2050. B4 contributes to a lesser extent, while B2 and B3 reflect the modelling relationship with production-stage impacts.

The results also indicate a relatively uniform response between the MFH cases, suggesting a lower sensitivity to typological variation within this building class.

Table 21: Average reduction of GWP in MFH typologies, due to WLC measure 5.2 to 2030 & 2050

Typology	A1-A3	B2	B3	B4	TOT
MFH 2030	18%	17%	14%	4%	**9%**
MFH 2050	49%	45%	45%	13%	**24%**

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OFF typologies - 2030 & 2050

For OFF typologies, the target values confirm the relevance of measure 5.2 also for non-residential buildings. As reported in Table 22, the reduction of module A1-A3 is 20% in 2030 and 53% in 2050, leading to an average overall WLC GWP reduction of 10% in 2030 and 28% in 2050. Compared with residential typologies, OFF shows a higher contribution from B4, reflecting the greater relevance of replacement cycles in office buildings, where finishes, technical systems and non-structural components are generally subject to more frequent replacement.

Table 22: Average reduction of GWP in OFF typologies, due to WLC measure 5.2 to 2030 & 2050

Typology	A1-A3	B2	B3	B4	TOT
OFF 2030	20%	18%	18%	8%	**10%**
OFF 2050	53%	48%	48%	28%	**28%**

Cross-typology interpretation

Overall, the target of WLC measure 5.2 can be primarily defined as a reduction of production-stage impacts. Across the assessed typologies, the average reduction of A1-A3 ranges from **17–20% in 2030** to **47–53% in 2050**. The corresponding overall WLC GWP reduction ranges from **9–10% in 2030** to **24–28% in 2050**.

The comparison across typologies also shows that the contribution of B4 remains lower in residential buildings, while it becomes more relevant in OFF typologies. This is confirmed by the GWP/HFA reductions reported in **Table 23**: OFF achieves the highest overall reduction, equal to **-241 $kgCO_2eq/HFA$ at 2030** and **-625 $kgCO_2eq/HFA$ at 2050**, mainly due to the higher B4 contribution. This indicates a greater reduction potential for office buildings due to the higher contribution of replacement-related impacts.

The improvements recorded in modules **B2 and B3** are a modelling consequence of the assumptions adopted in the assessment framework, see **D7.20**, whereby the impacts of these modules are derived as a fixed proportion of **A1-A3**. The observed reductions therefore reflect this parametric dependency rather than a direct effect of the decarbonisation strategy itself. Nevertheless, analogous reductions in the carbon intensity of maintenance and repair activities are considered plausible, as the materials required for such operations are expected to follow the same decarbonisation trajectory modelled for the production stage. Given this consideration, and acknowledging that the contribution of these modules to the overall WLC balance is limited, their improved values are retained in the assessment.

The reductions reported in **Table 23** are expressed in terms of **GWP/HFA** for the individual LCMs relative to the baseline. Only effective reductions are shown, excluding those resulting solely from the assumptions adopted. Similarly, improvements observed in **A5** should be considered as consequences of the WLC modelling approach rather than direct effects of the measure in construction practice.

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Table 23: Average GWP/HFA reduction achieved with measure 5.2, rounding down

Year	Typology	A1-A3 [$kgCO_2eq$ /HFA]	B2 [$kgCO_2eq$ /HFA]	B3 [$kgCO_2eq$ /HFA]	B4 [$kgCO_2eq$ /HFA]	TOT [$kgCO_2eq$/HFA]
2030	SFH	-181	-2	-1	-14	**-198**
	MFH	-172	-2	-0	-23	**-196**
	OFF	-186	-2	-1	-52	**-241**
2050	SFH	-494	-6	-1	-54	**-555**
	MFH	-451	-5	-1	-74	**-531**
	OFF	-489	-6	-1	-170	**-625**

To convert the absolute reductions reported in Table 23 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,357** for SFH, **0,465** for MFH, **0,587** for OFF. Percentage reductions shown in Table 20, 21, 22 are not affected by this conversion.

Target definition for WLC measure 5.3: Carbon capture, utilisation and storage in production

The target definition for WLC measure 5.3 is based on the reductions obtained from the application of CEM-CCS to cement production in the assessed case study, **IT_MFH_01_N_E_3**. As the measure acts directly on cement production, the primary target concerns module **A1-A3**.

As reported in **Figures 40 and 41**, the results indicate a reduction of **36.1%** in module **A1-A3**, confirming that the main target of the measure is the decarbonisation of cement production. This reduction contributes to an overall **WLC GWP reduction of 16.9%** at the 2050 horizon. A smaller reduction is observed in module **B4**, equal to **6.3%**, which can be interpreted as an indirect effect linked to the use of lower-carbon cement in replacement-related processes.

The reduction of the individual LCMs compared with the baseline is reported in **Table 24**. The values highlighted in grey indicate the improvements resulting from the assumptions adopted by the Italian consortium and described in **D7.20**, which are therefore not directly attributable to the decarbonisation strategy itself.

Table 24: Average reduction of GWP due to WLC measure 5.3 (on MFH)

Typology	A1-A3	A5	B2	B3	B4	C1	TOT
(MFH)	36%	34%	33%	33%	6%	22%	**17%**

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The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation.

The improvements recorded in modules B2 and B3 are a modelling consequence of the assumptions adopted in the assessment framework, described in **D7.20**, whereby the impacts of these modules are derived as a fixed proportion of A1-A3.

The observed reductions therefore reflect this parametric dependency rather than a direct effect of the decarbonisation strategy itself. Nevertheless, analogous reductions in the carbon intensity of maintenance and repair activities are considered plausible, insofar as the materials required for such operations are reasonably expected to follow the same decarbonisation trajectory modelled for the production stage. Given this consideration, and acknowledging that the contribution of these modules to the overall WLC balance is limited in magnitude, their improved values are retained in the assessment. The reductions reported in Table 25 are expressed in terms of GWP/HFA for the individual LCMs relative to the baseline. Only **effective reductions** are shown. Reductions resulting solely from modelling assumptions are not retained from the effective reduction calculation and marked as "**NR**" in the table.

Table 25: Average GWP/HFA reduction achieved with measure 5.3 (on MFH), rounding down

WLC Measure	A1-A3 [kgCO2eq/HFA]	A5 [kgCO2eq/HFA]	B2 [kgCO2eq/HFA]	B3 [kgCO2eq/HFA]	B4 [kgCO2eq/HFA]	C1	TOT [kgCO2eq/HFA]
5.3	-427	NR	-5	-1	-52	NR	**-484**

To convert the absolute reductions reported in Table 25 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,506**. Percentage reductions shown in Table 24 are not affected by this conversion.

7.1.4. Strategy 6 target definition: Reduce emissions from transport of materials and construction products

The target definition for Strategy 6 is based on the reductions observed for the transport-related WLC measures, with particular reference to module A4, where the impacts associated with the transport of construction materials and products to the building site are accounted for. Since the strategy acts on transport distances and transport modes, the primary target concerns the reduction of A4 impacts, while additional effects observed in other modules are interpreted according to the modelling assumptions adopted in the WLC assessment.

The following sections define the targets for measures 6.1 and 6.2, distinguishing between the direct reductions attributable to transport-related interventions and the secondary effects propagated to other LCMs.

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Target definition for WLC measure 6.1: reducing the distance materials travel to construction sites by favouring local sourcing

The target definition for WLC measure 6.1 is based on the reductions obtained by reducing the transport distance of selected construction materials and products through local sourcing. Since the measure acts directly on transport to the construction site, the primary target is associated with module A4.

As reported in Table 26, the application of measure 6.1 leads to a reduction of 8.5% in module A4, which accounts for approximately 78% of the total GWP benefit. This confirms that the main effect of the measure is concentrated on transport-related impacts. The corresponding overall WLC GWP reduction is 1.4%, reflecting the selective scope of the intervention, as only a limited number of material categories are affected by the local sourcing scenario.

A secondary contribution is observed in module B4, with a reduction of 1.2%, corresponding to approximately 16% of the total benefit. This effect is linked to the propagation of transport-related assumptions into replacement processes, where substituted materials partially inherit the sourcing assumptions applied to the original materials.

The reduction observed in module C1 is limited and should be interpreted in relation to the modelling assumptions adopted in the assessment framework, as described in **D7.20**. It should therefore not be considered as a direct effect of the decarbonisation strategy itself.

On this basis, the target for WLC measure 6.1 can be defined as an 8.5% reduction of A4 impacts, corresponding to an overall WLC GWP reduction of 1.4% for the assessed case. A broader implementation of local sourcing, extended to a wider range of construction materials and products, would be expected to increase the overall WLC reduction potential.

Table 26: Reduction of GWP due to WLC measure 6.1 (on SFH)

Typology	A4	A5	B2	B3	B4	C1	C2	TOT
(SFH)	9%	0%	2%	2%	1%	1%	0%	**1,4%**

The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation.

GWP/HFA reductions achieved with this measure are presented in Table 28 together with measure 6.2.

Target definition for WLC measure 6.2: employing low-carbon transportation alternatives

The target definition for WLC measure 6.2 is based on the reductions obtained by replacing conventional transport modes with lower-carbon transportation alternatives. Compared with measure 6.1, which acts on transport distances, measure 6.2 produces a higher overall WLC GWP reduction, equal to 4.7% compared with 1.4%. This is because the reduction in the transport emission factor applies across all transported material categories, rather than being limited to selected materials or products.

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As reported in Table 27, the main reduction directly attributable to the measure is observed in module A4, which decreases by approximately 23% and represents 60.8% of the total GWP benefit. This confirms that the primary target of measure 6.2 is the decarbonisation of transport processes associated with the delivery of materials and products to the construction site.

A relevant direct effect is also observed in module C2, which decreases by approximately 23% and represents 14% of the total benefit. This result is consistent with the scope of the module, as C2 accounts for transport to waste processing and therefore responds directly to changes in the transport emission factor. Module B4 also contributes to the reduction, although to a lesser extent, with a decrease of approximately 2%, corresponding to 6.9% of the total benefit. This reflects the role of transport processes in replacement-related activities.

The reductions observed in modules A5, B2/B3 and C1 are instead linked to the modelling assumptions adopted in the WLC assessment framework, as described in **D7.20**, and should therefore not be considered as direct effects of the decarbonisation strategy itself.

Table 27: Reduction of GWP due to WLC measure 6.2 (on SFH)

Typology	A4	A5	B2	B3	B4	C1	C2	TOT
(SFH)	23%	6%	5%	5%	2%	5%	23%	**5%**

The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation.

The reductions reported in Table 28 are expressed in terms of GWP/HFA for the individual LCMs relative to the baseline. Only **effective reductions** are shown. Reductions resulting solely from modelling assumptions are not retained from the effective reduction calculation and marked as "**NR**" in the table. In this perspective, measure 6.2 achieves a total reduction of -123 $kgCO_2eq/HFA$, compared with -42 $kgCO_2eq/HFA$ for measure 6.1. This confirms that, for the assessed case, low-carbon transportation alternatives provide a higher reduction potential than local sourcing alone.

Table 28: GWP/HFA reduction achieved with measure 6.1, 6.2 (on SFH), rounding down

WLC measure	A4 [kgCO2 eq/HFA]	A5 [kgCO2 eq/HFA]	B2 [kgCO2 eq/HFA]	B3 [kgCO2 eq/HFA]	B4 [kgCO2 eq/HFA]	C2 [kgCO2 eq/HFA]	C1 [kgCO2 eq/HFA]	TOT [kgCO2eq/ HFA]
6.1	-35	NR	NR	NR	-7	-0	NR	**-42**
6.2	-91	NR	NR	NR	-10	-21	NR	**-123**

To convert the absolute reductions reported in Table 28 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,301**. Percentage reductions shown in Table 26, 27 are not affected by this conversion.

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On this basis, the target for WLC measure 6.2 can be defined as a **23% reduction of transport-related impacts in modules A4 and C2**, corresponding to an overall **WLC GWP reduction of approximately 5%**. The results indicate that transport mode decarbonisation represents a more impactful lever than distance reduction for the building typologies and material compositions modelled in this assessment, provided that lower-emission vehicles are effectively available and adopted in practice.

7.1.5. Strategy 8 target definition: Reduce emissions from traditionally high impact construction materials

Target definition for WLC measure 8.2: Use of materials with high recycled content

The target definition for WLC measure 8.2 is based on the reductions obtained through the use of materials with higher recycled content. Since the measure acts on the carbon intensity of material production, the primary target is associated with module A1-A3. Additional effects are observed in modules linked to maintenance, repair and replacement processes, while modules independent of material production datasets remain unchanged.

SFH typologies

For the SFH typologies, the overall WLC GWP reduction ranges from **6% to 10%**. The target is mainly driven by module **A1-A3**, which accounts for approximately **74%** of the total absolute benefit. This is consistent with the scope of the measure, which directly affects the production-stage impacts of materials.

Module **B4** contributes approximately **10–13%** of the total benefit, with a reduction of **3–7%** compared with the baseline. This indicates that the effect of the measure also propagates to replacement processes, although to a lesser extent than in A1-A3. The different response of B4 reflects the fact that components with higher replacement frequency do not necessarily correspond to the material families showing the largest reductions in the production dataset. Therefore, while the use of materials with higher recycled content is effective, complementary strategies addressing component durability remain relevant.

The improvement observed in **A5** is attributable to the calculation assumptions adopted for this module and should not be considered a direct effect of the measure. The SFH results should also be interpreted in relation to the specific material composition of the analysed case studies, particularly the relevance of concrete, which strongly influences the magnitude of the reduction achieved in A1-A3.

MFH+HOS typologies

For the MFH typologies, module **A1-A3** is again the main contributor to the total GWP reduction, accounting for approximately **74–84%** of the total absolute benefit. The wider range observed between the two MFH cases reflects differences in material composition and, consequently, a different sensitivity to changes in the GWP dataset.

Module **B4** contributes approximately **2–3%** of the total benefit, with a reduction of **2%** compared with the baseline. This more limited response suggests that, in the

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analysed MFH cases, components subject to periodic replacement are less strongly associated with the material families affected by the recycled-content dataset. As for the SFH typologies, this confirms that B4 remains a relevant module in the life-cycle profile and that material decarbonisation should be considered together with strategies addressing durability and replacement frequency.

As for SFH, the improvement observed in **A5** is linked to the calculation assumptions adopted for the module and does not represent a direct benefit of the measure. The greater heterogeneity observed between the two MFH cases suggests that caution is needed when generalising the results to the whole typological class.

OFF typologies

For the OFF typologies, the overall WLC GWP reduction ranges from **3% to 5%**. The reduction is mainly driven by module **A1-A3**, which contributes approximately **68–75%** of the total absolute benefit, confirming the relevance of production-stage impacts also for non-residential buildings.

Compared with the residential typologies, module **B4** has a more relevant contribution, accounting for approximately **12–21%** of the total benefit, with a reduction of **2–5%** compared with the baseline. This reflects the higher relevance of replacement cycles in office buildings, where components subject to periodic replacement have a proportionally greater influence on the WLC profile.

The variability between the two OFF cases is more limited than for MFH, suggesting a more homogeneous material composition within the analysed office cases, although the sample remains limited. As for the residential typologies, the improvement observed in **A5** is linked to calculation assumptions and is not considered a direct effect of the measure.

Therefore, it should be excluded from the benefits directly attributable to WLC measure 8.2 in the following analyses.

The reduction of the individual LCMs compared with the baseline is reported in Table 29. The values highlighted in grey indicate the improvements resulting from the assumptions adopted by the Italian consortium and described in **D7.20**, which are therefore not directly attributable to the decarbonisation strategy itself.

Table 29: Average reduction of GWP in SFH and MFH typologies, due to WLC measure 8.2

Typology	A1-A3	A5	B2	B3	B4	TOT
SFH	15%	9%	12%	12%	5%	**7%**
MFH	14%	9%	13%	13%	2%	**7%**
OFF	9%	9%	8%	8%	3%	**4%**

The improvements recorded in modules B2 and B3 are a modelling consequence of the assumptions adopted in the assessment framework (**D7.20**), whereby the impacts of these modules are derived as a fixed proportion of A1–A3. The observed reductions reflect this parametric dependency rather than a direct effect of the decarbonisation strategy itself.

Nevertheless, analogous reductions in the carbon intensity of maintenance and repair activities are considered plausible, insofar as the materials required for such operations are reasonably expected to follow the same decarbonisation trajectory

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modelled for the production stage. Given this consideration, and acknowledging that the contribution of these modules to the overall WLC balance is limited in magnitude, their improved values are retained in the assessment.

Table 30 reports the reduction potential of WLC measure 8.2, expressed in terms of GWP/HFA and disaggregated by LCM. In this calculation, only the modules directly affected by the introduction of materials with higher recycled content are considered, excluding reductions resulting solely from methodological assumptions. Only **effective reductions** are shown. Reductions resulting solely from modelling assumptions are not retained from the effective reduction calculation and marked as "**NR**" in the table.

Table 30: Average GWP/HFA reduction achieved with measure 8.2, rounding down

Typology	A1-A3 [kgCO2eq/ HFA]	A5	B2 [kgCO2eq/ HFA]	B3 [kgCO2eq/ HFA]	B4 [kgCO2eq/ HFA]	TOT [kgCO2eq/HFA]
SFH	-154	NR	-2	-0	-24	**-180**
MFH	-119	NR	-1	-0	-13	**-134**
OFF	-82	NR	-1	-0	-21	**-105**

To convert the absolute reductions reported in Table 30 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,357** for SFH, **0,465** for MFH and **0,587** for OFF. Percentage reductions shown in Table 29 are not affected by this conversion.

This makes it possible to compare the benefit directly attributable to the measure across the different building typologies. In particular, the results reported in Table 30 show that the highest absolute reduction is achieved for the SFH typologies, with a total reduction of **-180 $kgCO_2eq/HFA$**, mainly driven by module **A1-A3**. The corresponding reductions are **-134 $kgCO_2eq/HFA$** for **MFH** and **-105 $kgCO_2eq/HFA$** for **OFF**.

This confirms that the reduction potential of measure 8.2 is closely linked to the material composition of the case studies and, in particular, to the weight of high-impact materials affected by the recycled-content dataset.

7.1.6. Strategy 9 target definition: Reduce operational carbon emissions

Target definition for WLC measure 9.5: increase renewable energy

The target definition for WLC measure 9.5 is based on the projected increase in the renewable share of the Italian electricity mix. Since the measure acts on the carbon intensity of operational energy use, the primary target is associated with the reduction of emissions in module **B6**.

The modelling evaluates how the reduction of B6 impacts modifies the balance between **Operational Carbon (OC)** and **Embodied Carbon (EC)** across the different building typologies analysed. The strategy reduces the relative weight of OC in all typologies: from **15% to 12%** for **SFH**, from **27% to 21%** for **MFH+HOS**, from **56% to 49%** for **OFF**, and from **11% to 8%** for **XTR/EDU**. Consequently, the relative weight of Embodied Carbon increases across all categories as a result of the reduction of the

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operational component in the overall balance, and not because of an increase in embodied impacts.

The most pronounced effect is observed in the **OFF** typology, where Operational Carbon decreases by **7 percentage points**. This case is also the most significant from an interpretative perspective: in the baseline scenario, office buildings were the only typology characterised by a prevalence of Operational Carbon over Embodied Carbon, with a distribution of **44% EC** and **56% OC**. Following the application of the strategy, the balance approaches a substantially balanced condition, with **51% EC** and **49% OC**. The **OC/EC ratio** decreases from **127.3** to **96.1**, falling below the threshold of **100**, above which OC exceeds EC. This indicates that the decarbonisation of the electricity grid modifies the relative hierarchy between Operational Carbon and Embodied Carbon for the office typology.

For the **MFH+HOS** typology, the Operational Carbon share decreases by **6 percentage points**, from 27% to 21%. The **OC/EC ratio** also decreases, from **37.0** to **26.6**, corresponding to a relative reduction of 28.1%. However, for this typology, embodied carbon was already the dominant contributor in the baseline scenario and accounts for an even greater relative share following the decarbonisation of the electricity grid.

The measure therefore contributes to reducing the operational component, but, unlike the OFF typology, it does not lead to a shift in the prevailing carbon balance, which remains dominated by Embodied Carbon.

For **SFH**, the Operational Carbon share decreases by **3 percentage points**, from **15% to 12%**. The **OC/EC ratio** decreases from **17.6** to **13.6**, corresponding to a relative reduction of **22.7%**. Despite this reduction, the carbon balance of this typology remains dominated by **Embodied Carbon**. The measure therefore contributes to reducing the operational component, but does not modify the overall structure of the WLC balance.

For **XTR/EDU**, the Operational Carbon share also decreases by 3 percentage points, from 11% to 8%. The OC/EC ratio decreases by 29.6%, although this relative variation should be interpreted in light of the already limited contribution of OC in the baseline scenario. The results are also influenced by the specific characteristics and limited number of case studies included in this category. Overall, the measure further reduces an operational component that was already secondary compared with Embodied Carbon.

Overall, WLC measure **9.5** defines a target for reducing the operational component associated with module **B6**, with effects that vary across the different typologies. The most pronounced effect is observed for **OFF**, where the **OC/EC ratio** shifts from an OC-dominant condition to a slightly EC-dominant condition. For **MFH+HOS** and **XTR/EDU**, the measure reduces the operational component within a carbon balance already characterised by the prevalence of Embodied Carbon. For **SFH**, the effect is more limited, confirming that, in typologies already strongly dominated by EC, grid decarbonisation alone has a lower reduction potential on the overall WLC balance.

These results should be interpreted considering that module B6 may include different energy carriers depending on the case study, such as electricity, gas or other fuels. In WLC measure 9.5, the assessment only considers the effect of the decarbonisation of the national electricity grid. Therefore, the measure directly reduces only the electricity-related share of operational energy use, while emissions associated with other energy carriers remain unchanged. As a result, the effectiveness of the measure depends on the extent to which each building typology relies on electricity within its operational energy mix.

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Once the operational contribution associated with electricity use is reduced, further mitigation should increasingly focus on **EC**, through actions addressing materials, building components, construction systems and design choices across the life cycle.

The reductions reported in **Table 32** are expressed as percentage variations relative to the total baseline WLC-GWP of each typology. Since WLC measure 9.5 acts only on the electricity-related share of module B6, the values represent the contribution of the B6 reduction to the overall WLC-GWP reduction, rather than the percentage reduction of module B6 itself.

Table 31: Average reduction of GWP in SFH, MFH and OFF typologies, due to WLC measure 9.5

Typology	B6	TOT
SFH	26%	**4%**
MFH	33%	**8%**
OFF	27%	**15%**

The reductions reported in **Table 31** are expressed in terms of **GWP/HFA** for module **B6** relative to the baseline. Since measure **9.5** acts only on the electricity component of operational energy use, the total reduction reported in Table 32 corresponds entirely to the reduction in module **B6**.

Table 32: Average GWP/HFA reduction achieved with measure 9.5, rounding down

Typology	B6 [kgCO2eq/HFA]	TOT [kgCO2eq/HFA]
SFH	-87	**-87**
MFH	-222	**-222**
OFF	-703	**-703**

To convert the absolute reductions reported in Table 32 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,483** for SFH, **0,705** for MFH and **0,487** for OFF. Percentage reductions shown in Table 31 are not affected by this conversion.

The results reported in **Table 32** show that the highest absolute reduction is achieved for the **OFF** typology, with a decrease of **-703 $kgCO_2eq/HFA$**. The corresponding reductions are **-222 $kgCO_2eq/HFA$** for **MFH** and **-87 $kgCO_2eq/HFA$** for **SFH**. These values confirm that the mitigation potential of the measure differs across typologies, with the highest absolute benefit observed where operational electricity use has a greater relevance in the baseline scenario.

This confirms that the target of WLC measure **9.5** can be defined as the reduction of OC emissions associated with electricity consumption.

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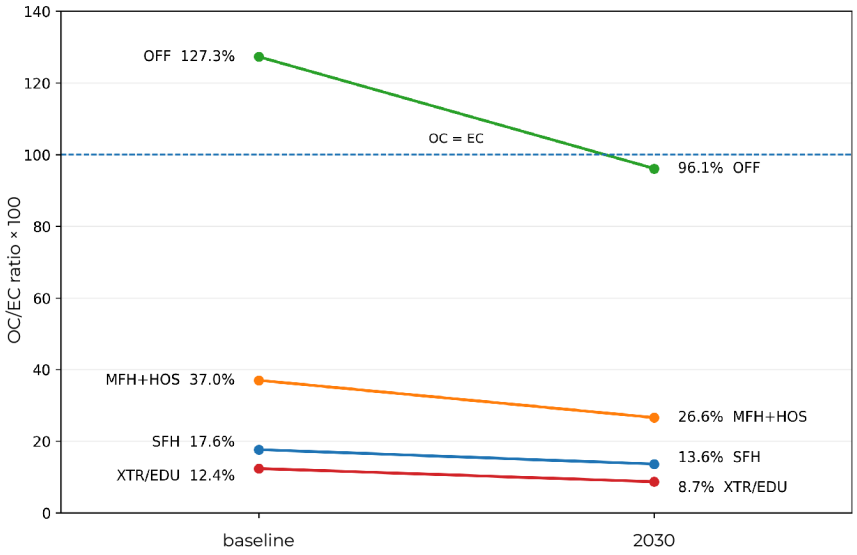


Figure 59: Effects of measure on OC/EC ratio

Figure 59 summarises the effect of WLC measure 9.5 on the OC/EC ratio across the analysed typologies. The figure confirms that OFF is the only typology shifting from an OC-dominant condition to a slightly EC-dominant condition, while the other typologies remain clearly dominated by EC both before and after the application of the measure.

7.1.7. Strategy 11 target definition: Use of carbon dioxide removal (CDR) solutions

Target definition for WLC measure 11.1: Green roofs and/or green façades

The target definition for WLC measure 11.1 is based on the additional negative contribution introduced in module B1 through the application of a green roof solution to the renovation case study IT_MFH_11_R_E_3. Since module B1 is not present in the baseline scenario, the target is not expressed as a reduction of an existing baseline module, but as an additional contribution to the overall WLC reduction achieved in the remodelling scenario.

The reduction reported in **Table 33** is expressed as a percentage variation relative to the total baseline WLC-GWP of the assessed case study. Since WLC measure 11.1 introduces an additional negative contribution in module B1, the value represents the contribution of vegetation-related CO_2 uptake to the overall WLC-GWP reduction, rather than the reduction of an existing baseline module.

Table 33: Overall WLC-GWP reduction due to WLC measure 11.1 (on MFH) [%]

Typology	B1 [kgCO2eq/HFA]	TOT [kgCO2eq/HFA]
(MFH)	No B1 value for baseline	**-3%**

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The measure was assessed on a single representative residential typology, since its effect was considered mainly related to the specific design or modelling assumption rather than to typological variation.

As reported in Table 34, the measure achieves a reduction of 18 $kgCO_2eq/HFA$, entirely associated with module B1. This corresponds to an overall GWPtot reduction of approximately 3% for the assessed case study.

Table 34: Average GWP/HFA reduction achieved with measure 11.1 (on MFH), rounding down

WLC measure	B1 [kgCO2eq/HFA]	TOT [kgCO2eq/HFA]
11.1	-18	**-18**

To convert the absolute reductions reported in Table 34 from $kgCO_2eq/m^2$ HFA to $kgCO_2eq/m^2$ GFA, the values should be multiplied by the HFA/GFA **conversion factor**. For this measure, the conversion factor is **0,575**. Percentage reductions shown in Table 33 are not affected by this conversion.

The result provides a quantitative reference for interpreting the role of greenery-based CDR solutions within the broader WLC balance. Although the magnitude of the reduction is limited, the contribution is relevant because it relies on a mechanism different from the other strategies assessed in the report. While measures targeting modules such as **A1-A3**, **A4** or **B6** act on material production, transport or operational energy processes, WLC measure **11.1** introduces a negative contribution associated with biogenic carbon uptake through vegetation.

For this reason, the contribution of **B1** should be interpreted as complementary to the other WLC measures, rather than as a substitute for strategies reducing emissions in the main LCMs. Its role is therefore to provide an additional reduction within the overall WLC balance, where technically feasible and compatible with the building context.

The result should also be read in relation to the technical configuration of the assessed case study. The green roof system applied to **IT_MFH_11_R_E_3** is a lightweight intensive solution, with a maximum saturated load of **≤282 kg/m²**, installed on an existing building without structural reinforcement. This aspect is particularly relevant for renovation contexts, since the benefit associated with **B1** is achieved without requiring additional structural works that could otherwise increase embodied impacts in modules **A1-A3** and **A5**.

Overall, the target of WLC measure **11.1** can be defined as an additional contribution of **-18 $kgCO_2eq/HFA$** in module **B1**, corresponding to an overall **GWPtot reduction of approximately 3%** for the assessed renovation case study. Further assessment is required to evaluate the impacts associated with maintenance operations and to understand the applicability of this measure across other building typologies and green roof or façade configurations.

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7.2. Integrated results of the WLC measures

This section presents an integrated interpretation of the results obtained from the quantitative assessment of the WLC measures. The analysis is structured into two complementary levels.

First, the results are aggregated by **WLC measure**, in order to compare the reduction potential of the individual measures assessed. Within this aggregation, the results are further interpreted according to two perspectives: the distribution of benefits across the main life-cycle stages and the differences observed across building typologies.

Second, the results are aggregated according to the **ASI framework**, considering the selected pathways and the corresponding strategy packages. This second level of aggregation makes it possible to assess how the combined measures contribute to the expected reduction potential and in which life-cycle stages the benefits are mainly concentrated.

Overall, these elaborations provide a synthetic and integrated reading of the modelling outcomes and support the identification of the measures, pathways and strategy packages with the highest reduction potential. They also provide the interpretative basis for the conclusions developed in **Chapter 8** of this report.

7.2.1. Aggregated results by WLC measure, life-cycle stage and building typology

Table 35 provides an overall synthesis of the results obtained for the assessed WLC measures. For each measure, the table reports the corresponding typology where the assessment was carried out on specific building categories.

For WLC measures where the remodelling was performed on a single building typology because the effect of the measure was considered not to be significantly influenced by building typology, the typology is still reported in brackets. This distinction makes it possible to differentiate between typology-specific results and results derived from a representative case study, where the effect of the measure is assumed to be largely independent of the building typology analysed.

As reported in Table 35, the improvements are expressed as percentage reductions in order to support comparability across typologies and measures. This avoids distortions that may arise when comparing absolute values, such as $kgCO_2eq/m^2$ HFA, which are strongly influenced by baseline impacts, building geometry and material quantities. Percentage reductions therefore provide a more consistent basis for comparing the relative effectiveness of each WLC measure across different typological contexts. In this aggregation, the **percentage reductions** reported under the **life-cycle stage groups** represent the share of the **total WLC-GWP reduction** generated by each stage group. They should therefore not be interpreted as percentage reductions relative to the original baseline value of the corresponding module or module group. For typologies reported in brackets, the remodelling was carried out on a single **representative case study**, either because the effectiveness of the measure was considered independent of building typology or due to technical feasibility constraints.

The reference year reported in Table 35 refers to the time horizon explicitly adopted in the modelling of each WLC measure. Where no year is indicated, the measure is not based on a time-dependent scenario, but on design, supply-chain or

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case-study-specific assumptions that may be applied across different time horizons, subject to compatibility with the other measures considered.

Table 35: Overview of GWP reduction by LCM group and WLC measure [%]

WLC measure	Typology	A1-A3	A4-A5	B1-B6	C1-C4	Total
2.4.a (no specific year)	*(MFH)**	-	-	-4%	-	**-4%**
2.4.b (no specific year)	*(MFH)**	-	-	-1%	-	**-1%**
5.2 (2030)	**SFH**	-7%	-	-1%	-	**-9%**
	MFH	-7%	-	-1%	-	**-9%**
	OFF	-7%	-	-2%	-	**-10%**
5.2 (2050)	**SFH**	-20%	-	-2%	-	**-25%**
	MFH	-19%	-	-3%	-	**-24%**
	OFF	-18%	-	-7%	-	**-28%**
5.3 (2050)	*(MFH)**	-13%	-	-2%	-	**-17%**
6.1 (no specific year)	*(SFH)**	-	-1%	-0%	-	**-1%**
6.2 (2030)	*(SFH)**	-	-3%	-0%	-1%	**-5%**
8.2 (2030)	**SFH**	-6%	-	-1%	-	**-7%**
	MFH	-5%	-	-1%	-	**-7%**
	OFF	-3%	-	-1%	-	**-4%**

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9.5 (2030)	**SFH**	-	-	-26%**	-	**-4%**
	MFH	-	-	-33%**	-	**-8%**
	OFF	-	-	-27%**	-	**-15%**
11.1 (no specific year)	*(MFH)**	-	-	X	-	**-3%**

*Measure assessed on a single representative case study or typology because the effect is considered mainly related to the specific design or modelling assumption rather than to typological variation. The result is used as a reference value for all the building categories considered in the report.

**The contribution shown is entirely associated with a reduction on module B6.

X: Not assessed due to the lack of a baseline value.

The **Table 35** supports a cross-cutting interpretation of the results by relating the reduction potential of the different WLC measures to the main LCM groups and to the building typologies analysed. The interpretation is therefore structured at two levels: first, the distribution of benefits across the life-cycle stages; second, the different responses observed across building typologies.

Reduction patterns across LCM

Modules **A1-A3** represent the life-cycle stage where the main reduction potential is concentrated among the assessed measures and show a clear dependency on the time horizon considered. In particular, WLC measure **5.2** shows an increase in reduction potential between **2030** and **2050**, moving **from -7% to -20% for SFH** and **from -7% to -18% for OFF**. This trend reflects the role of the decarbonisation of material production processes and the progressive uptake of lower-carbon technologies across the relevant supply chains.

Alongside the production stage, the use stage, represented by modules **B1-B6**, constitutes a further area of reduction, although with greater heterogeneity. This range includes measures of different nature: measure **2.4** acts on the reduction of replacements through increased component durability; measure 9.5 addresses the reduction of operational emissions associated with electricity consumption through the decarbonisation of the national electricity mix; measure 11.1 introduces a negative contribution related to CO_2 uptake from building-integrated greenery solutions. The value reported for measure 9.5, marked with an asterisk, refers to the impact on OC.

Compared with the production and use stages, modules **A4-A5** and **C1-C4** show more limited reductions in absolute terms. These modules refer respectively to transport/construction process stages and end-of-life stages, and are mainly affected by measures **6.1** and **6.2.** This result is consistent with the lower weight of these modules in the baseline scenario. However, the lower absolute magnitude of the reductions should not be interpreted as an indicator of limited strategic relevance. A **total GWP** reduction of approximately **-1% to -4%** achieved through these modules

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should instead be assessed in relation to the reduction potential actually available in these life-cycle stages.

Reduction patterns across building typologies

The analysis by building typology shows how the effectiveness of the WLC measures varies according to the characteristics of the assessed building typologies. In particular, the comparison between WLC measure 8.2 (Use of materials with high recycled content) and WLC measure 9.5 (Increase renewable energy) highlights two opposite trends.

WLC measure 8.2, which aims to reduce the embodied impacts of construction materials through the use of materials with higher recycled content, shows progressively lower total reductions from **SFH** to **MFH** and **OFF**, with values of **-7%**, **-7%** and **-4%**, respectively. By contrast, **WLC measure 9.5**, which aims to reduce OC emissions through the decarbonisation of the national electricity mix, shows increasing reductions across the same typological sequence: **-4%** for **SFH**, **-8%** for **MFH** and **-15%** for **OFF**.

This comparison indicates that the effectiveness of each measure depends on the carbon profile of the building typology. Measures addressing embodied impacts, such as 8.2, tend to have a greater relative effect in typologies where material-related impacts have a higher weight. Measures addressing operational emissions, such as 9.5, become more effective in typologies where operational energy use has a greater contribution to the overall WLC balance, as observed for OFF.A similar typology-related effect can be observed for **WLC measure 5.2**, concerning the use of renewable energy sources in production. In the **2050** scenario, total reductions are relatively aligned across the three typologies, amounting to **-25%** for **SFH**, **24%** for **MFH** and **-28%** for **OFF**.

However, the internal distribution of the benefits differs. For OFF, the reduction in **A1–A3** is slightly lower than for the residential typologies, while the contribution from **B1–B6** is higher, mainly due to module **B4**, which reflects more frequent replacement cycles compared with residential buildings. This result suggests that, for non-residential buildings, which are characterised by more frequent replacements, the use of low-carbon materials can be particularly effective not only during the initial construction stage, but also at the time of component replacement.

Since measure 5.2 acts on the decarbonisation of construction material production, its effect also extends to the materials used in scheduled replacements, contributing to the slightly higher total reduction observed for OFF.

Finally, **WLC measure 5.2** – Renewable energy sources in production and WLC measure 5.3 – Carbon capture, utilisation and storage in production should be read together, as both act on the decarbonisation of high-impact material production processes. As indicated in the compatibility matrix presented in Section 7.3, these measures are mutually exclusive in the model because they act on the same supply chain and their effects cannot be combined. However, their reduction potential differs depending on the time horizon considered.

For MFH, measure 5.3 achieves a total reduction of **−17%**, which is higher than measure 5.2 in the 2030 scenario (−9%), but lower than measure 5.2 in the 2050 scenario (**−24%**). This comparison highlights a temporal difference between the two options. In the short term, carbon capture and storage applied to cement-based materials provides a higher immediate reduction. In the long term, however, the decarbonisation of the energy sources used in production processes, as modelled in measure 5.2, becomes more effective.

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7.2.2. Aggregated results by ASI framework and strategy packages

Following the assessment of individual WLC measures, the results are further organised according to the ASI framework. This **aggregation** provides an additional level of interpretation, aimed at linking the **quantified measures** to the broader decarbonisation pathways and **strategy packages** considered in the analysis (**Table 36**). The purpose of this step is not to provide a full assessment of all ASI pathways, but to **summarise** the **contribution** of the measures that were **quantitatively modelled** within the analysis. Accordingly, the results reflect the scope of the available modelling and should be interpreted as a quantitative overview of the assessed measures within each pathway.

The aggregation considers the following associations between strategy packages and WLC strategies: "Increase circularity and use of existing buildings" includes WLC strategies 2 and 8; "Reduce operational emissions" includes WLC strategy 9; "Increase use of improved materials" includes WLC strategy 5; and "Reduce transport and construction emission" includes WLC strategy 6. Strategy packages for which no quantitative values are reported were not modelled numerically within the analysed case studies. The **improvements** are expressed as percentage reductions in order to support comparability across pathways and strategy packages. For each strategy package, Table 36 reports the reduction associated with the main LCM groups and the corresponding total reduction.

Table 36: Overview of GWP reduction by ASI framework, strategy package and LCM group [%]

Approach	Strategy packages	A1-A3	A4-A5	B1-B6	C1-C4	ASI TOT
A	Increase circularity and use of existing buildings	-5%	-	-2%	-	**-7%**
	Increase use intensity	-	-	-	-	
S	Shift to low-carbon bio-based materials	-	-	-	-	-
I	Reduce operational emissions	-	-	-9%	-	**-20%**
	Increase use of improved materials	-7%	-	-2%	-	
	Reduce transport and construction emission	-	-2%	-0%	-	

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The aggregated results by **ASI pathway** show differences across the three approaches. The **Improve** pathway achieves the highest overall reduction, equal to **-20%**, followed by **Avoid**, with a reduction of **-7%**. For **Shift**, no quantitative assessment was produced. This difference in the quantified results should not be interpreted as indicating a lower intrinsic potential of the **Avoid** and **Shift** pathways. Rather, it reflects the greater methodological maturity and data availability for modelling measures associated with the **Improve** pathway, which are generally based on material or energy-source substitutions that can be more easily parameterised within the scope of this project.

Within the **Improve** pathway, the strategy package **"Reduce operational emissions"**, associated with **WLC strategy 9** and measure **9.5**, produces the highest contribution for a single module, with a reduction of **-9%** in **B1-B6**, specifically referring to module **B6**. This value is higher than the contribution of the strategy package **"Increase use of improved materials"**, associated with **WLC strategy 5**, which records a reduction of **-7%** in **A1-A3**.

The strategy package **"Reduce transport and construction emission"**, associated with **WLC strategy 6**, shows the lowest overall effect, equal to **-1%**. However, it is the only package affecting three module groups simultaneously: **A4-A5**, **B1-B6** and **C1-C4**. As already observed in **Section 7.2.1** for measures **6.1** and **6.2**, this result confirms that these modules, although having a lower weight in the baseline scenario, are still addressed by the measure through a contribution distributed across several life-cycle stages.

For the **Avoid** pathway, the strategy package **"Increase circularity and use of existing buildings"**, associated with **WLC strategies 2** and **8**, produces an overall reduction of **-7%**, distributed between **A1-A3** (**-5%**) and **B1-B6** (**-2%**). The second strategy package within the same pathway, **"Increase use intensity"**, does not report any quantitative value, since use-intensification strategies, such as space sharing or change of use, were not quantitatively modelled within the Italian case studies considered.

Finally, the **Shift** pathway does not include quantitative values for the strategy package **"Shift to low-carbon bio-based materials"**. The absence of data reflects the fact that, within the scope of the present study, the only strategy package associated with this pathway was not subject to quantitative analysis.

7.3. Combined implementation of WLC measures

Interactions between WLC measures and limitations of the single-strategy assessment approach

The decarbonisation strategies have so far been assessed individually through the quantification of the corresponding WLC measures, allowing the specific contribution of each intervention to be isolated and its effects on the different LCMs to be identified for the building typologies considered.

This approach represents a necessary methodological step for understanding the effectiveness of individual measures. However, in both design practice and technological development, decarbonisation strategies are generally implemented in combination, acting simultaneously on both the building system and the associated production processes.

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Assessing the combined effects of multiple WLC measures therefore represents a valuable step towards evaluating the decarbonisation potential achievable through the simultaneous implementation of different strategies. At the same time, combining different WLC measures may introduce methodological challenges.

The combined implementation of several measures does not necessarily produce a benefit equal to the sum of the individual contributions previously estimated, since interaction effects may occur. These may be either positive (synergies), when the combined application of two or more measures amplifies the overall benefit, or negative (antagonisms), when different measures act, at least partially, on the same emission reduction mechanism, resulting in overlapping effects and, consequently, a potential double counting of the estimated environmental benefits.

The objective of this section is therefore to explore the maximum decarbonisation potential among the assessed combinations through the combined implementation of the WLC measures quantitatively evaluated in this report by developing aggregated scenarios for the three building typologies considered.

7.3.1. Criteria for selecting the analysed combinations

For the purpose of assessing the effects of combining multiple **WLC measures**, the analysis was limited to those measures that were quantitatively assessed within the present study.

Since some combinations may present methodological or technological limitations, a **compatibility matrix** was developed to evaluate whether different measures could be implemented simultaneously without generating methodological overlaps or double counting of emission reductions. The resulting matrix is presented in Table 37**.**

The combinations were classified into three levels of compatibility:

- **Green cells:** fully compatible combinations;
- **Yellow cells:** combinations considered feasible, subject to specific methodological assumptions or requiring particular care in the interpretation of the results;
- **Red cells:** combinations not considered methodologically applicable.

The main methodological limitations **associated with the** yellow **and** red **combinations reported in** Table 37 **are described below.**

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Table 37: Compatibility matrix for combining WLC measures

	2.4	5.2	5.3	6.1	6.2	8.2	9.5	11.1
2.4								
5.2								
5.3								
6.1								
6.2								
8.2								
9.5								
11.1								

Measures 8.2 + 5.2. The increase in recycled content (WLC Measure 8.2) and the simultaneous decarbonisation of production processes through renewable energy sources (WLC Measure 5.2) act concurrently on the material production process. The use of secondary raw materials within a production process redesigned around a decarbonised energy mix may give rise to interaction effects that cannot be represented by the two models, which were developed and calibrated independently. Quantifying these effects would require process-specific data that are not available within the scope of the present study; consequently, this combination was not considered methodologically applicable.

Measures 5.2 + 5.3. Both measures act on the same segment of the production chain but according to technologically alternative approaches. Measure 5.2 reduces fossil emissions by modifying the energy mix used during material production, whereas Measure 5.3 acts downstream by capturing the CO_2 generated during the production process, including process-related emissions (e.g. those associated with limestone calcination). For this reason, the combination was not considered methodologically applicable.

Measures 5.3 + 8.2. This combination was considered feasible, taking into account a partial overlap associated with concrete. Consequently, the environmental impacts derived from Measure 5.3 were retained for concrete, whereas the updated environmental factors derived from Measure 8.2 were applied to all other materials.

Measure 2.4. This measure was developed for specific building components and therefore produces effects only in case studies where those components are present. Its applicability within the combined scenarios is consequently limited to the subset of case studies containing the building elements addressed by the measure.

Measure 11.1. This measure is not applicable to the entire sample of case studies, as it was developed and validated using a single case study already characterised by the presence of a green roof.

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Based on the compatibility assessment, the combination of WLC **Measures 6.1**, **6.2**, **9.5**, **5.3**, and **8.2** represents the **maximum combined decarbonisation scenario** assessed in this study. Measure 2.4 was included only partially, since its benefits depend on the presence of the specific building elements addressed by the measure in the analysed case studies.

Table 38: WLC measures included in the aggregated decarbonisation scenario

Measure	Description	Considered
2.4	Design for durability and maintainability of building components	(X)
5.2	Renewable energy sources in production	
5.3	Carbon capture, utilisation and storage in production	X
6.1	Use of locally sourced materials	X
6.2	Use of alternative fuels in transportation	X
8.2	Use of materials with high recycled content	X
9.5	Increase renewable energy	X
11.1	Green roofs and/or green façades	

GWP/mq			
SFH	IMPACT	STR. TYPE	RESULT
SFH_11	1	0,25	1,25
SFH_02	0,9	0,75	1,65
SFH_08	0,8	1	1,8
SFH_10	0,7	0,5	1,2
SFH_09	0,6	1	1,6
SFH_01	0,4	0	0,4

GWP/mq			
MFH+HOS	IMPACT	STR. TYPE	RESULT
MFH_02	1	1	2
MFH_19	1	0,75	1,75
HOS_03	1	0	1
MFH_01	0,8	1	1,8
HOS_05	0,7	0,75	1,45
MFH_27	0,6	1	1,6

GWP/mq			
OFF	IMPACT	STR. TYPE	RESULT
OFF_01	1	0,5	1,5
OFF_11	0,7	1	1,7
OFF_08	0,7	1	1,7
OFF_10	0,7	0,75	1,45
OFF_13	0,6	1	1,6
OFF_07	0,6	1	1,6

Figure 60. Multi-criteria ranking of new construction case studies by typology group for aggregates WLC measures.

7.3.2. Assessment results for WLC measure aggregated: 6.1 + 6.2 + 9.5 + 5.3 + 8.2 (+2.4)

For this aggregated modelling, results are reported for the three assessed typologies: SFH, MFH and OFF. For each typology, the comparison between the baseline scenario and the scenario resulting from the application of the measure is developed with reference to GWPtot impacts across the different LCMs. The results for SFH are reported in Figure 61, those for MFH in Figures 62, while the results for office buildings are reported in Figure 63.

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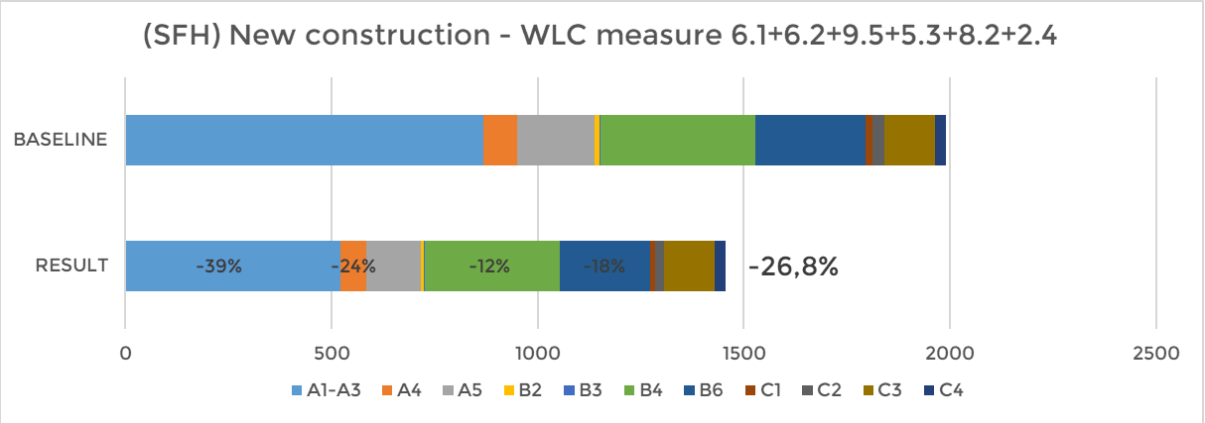


Figure 61: Comparison between the baseline and the new results for aggregated measures for SFH. GWPtot impacts are divided by LCMs

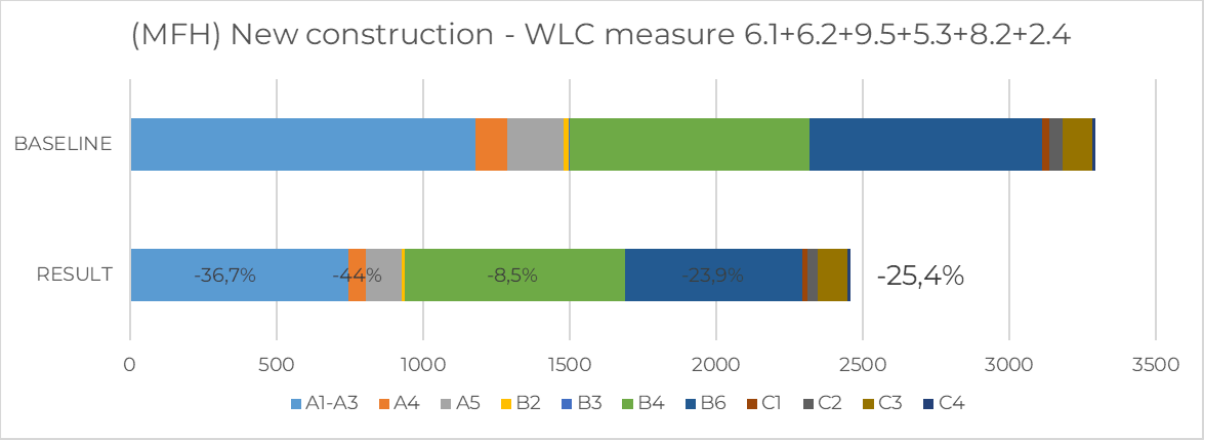


Figure 62: Comparison between the baseline and the new results for aggregated measures for MFH. GWPtot impacts are divided by LCMs

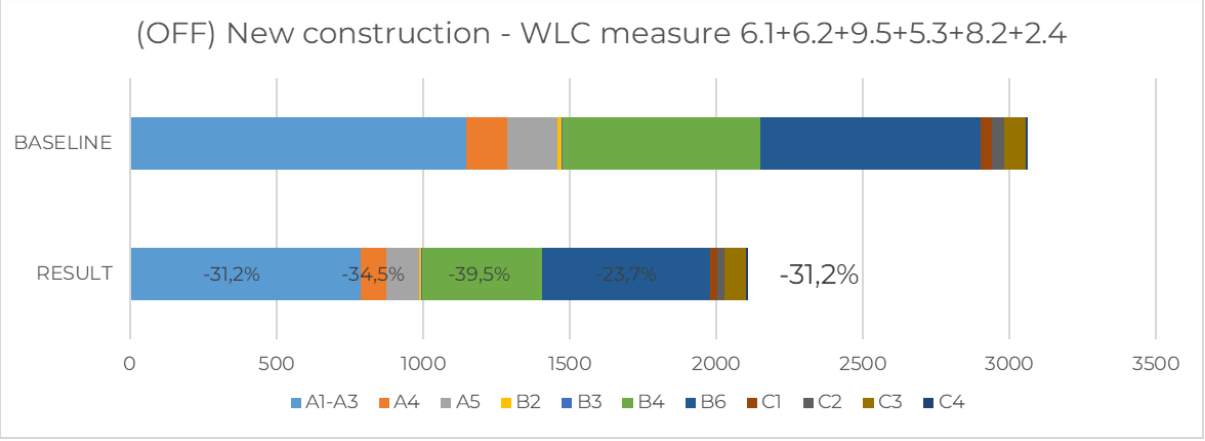


Figure 63: Comparison between the baseline and the new results for aggregated measures for OFF. GWPtot impacts are divided by LCMs

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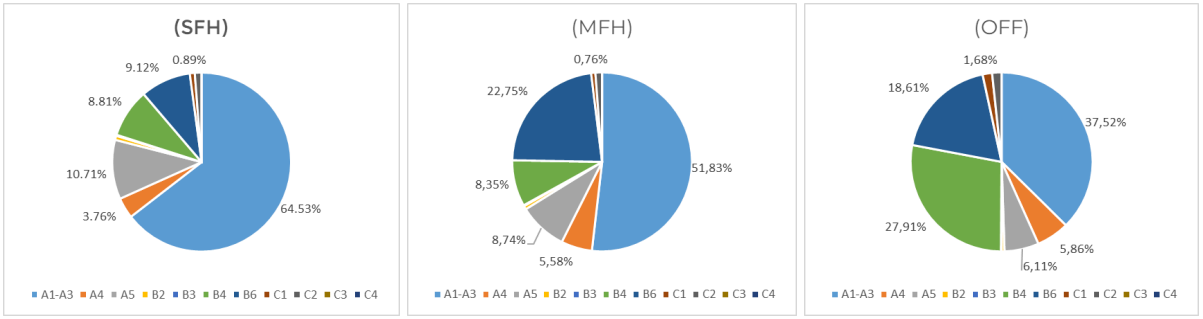


Figure 64: Absolute improvement (%) by LCM for SFH, MFH and OFF

The results show that the combination of multiple decarbonisation strategies leads to **comparable total GWP reductions** for the residential typologies, equal to **27%** for **SFH** and **25%** for **MFH**, despite a different distribution of the improvements across the Life Cycle Modules (LCMs). For office buildings (OFF), a greater overall reduction of **31%** was achieved. Finally, the results are aggregated by LCM and expressed as a percentage improvement relative to the total GWP. This analysis represents the potential improvement targets that can be achieved through the simultaneous implementation of the selected decarbonisation measures.

Table 39: GWP reduction achieved with measures 6.1 + 6.2 + 9.5 + 5.3 + 8.2 (+2.4), by LCM group [%]

Typology	A1-A3	A4-A5	B1-B6	C1-C4	TOT
SFH	-17%	-1%	-4%	-0%	**-27%**
MFH	-13%	-1%	-8%	-0%	**-25%**
OFF	-17%	-1%	-4%	-0%	**-31%**

7.3.3. Aggregated results by temporal scenario

An indicative estimate of the combined effects of the assessed WLC measures was developed for three **temporal scenarios**: **2030**, **2040** and **2050**.

These aggregated scenarios were derived by first considering the reference year or temporal scenario associated with each WLC measure, as reported in Table 35. Based on this information, specific assumptions were adopted to allocate the effects of each measure across the three temporal scenarios. In addition, potential incompatibilities among measures, as identified in the compatibility matrix reported in Table 37, were taken into account to avoid overlaps and potential double counting. The resulting temporal allocation of the assessed WLC measures, together with the treatment of potential incompatibilities among them is summarised in Table 40.

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Table 40. Temporal allocation and compatibility treatment of the WLC measures included in the aggregated scenarios.

WLC measure	2.4.a	2.4.b	5.2	5.2	5.3	6.1	6.2	8.2	9.5	11.1
Reference year	-	-	2030	2050	2050	-	2030	2030	2030	-
2030	○	○	●	—	—	○	●	×	●	○
2040	○	○	↔	—	—	○	→	×	→	○
2050	○	○	×	●	×	○	→	×	→	○

●	WLC measure linked to a **specific year**; the corresponding modelled value is assigned to that temporal scenario.
○	**Non-time-specific** WLC measure; the effect is assumed to remain constant across all temporal scenarios.
→	**Carry-forward value**: WLC measure modelled only for 2030; the 2030 reduction is retained unchanged in subsequent temporal scenarios.
↔	**Interpolated value:** an intermediate value is estimated between directly modelled temporal horizons.
—	**Long-term measure** not assigned: WLC measure modelled only for 2050 and not retroactively assigned to previous temporal scenarios.
×	WLC measure **excluded** from the aggregated scenario due to incompatibility or overlap with another measure, or because a directly modelled value for the corresponding temporal horizon is available.

Note: For WLC measure 5.2, which was directly modelled for both the 2030 and 2050 horizons, the 2040 value was estimated by linear interpolation between the two modelled values. Since 2040 lies halfway between 2030 and 2050, this value should be interpreted as an indicative estimate rather than a directly modelled result.

Where the compatibility matrix identifies mutually incompatible measures within the same temporal scenario, the measure with the highest total WLC-GWP reduction potential is retained as a conservative selection rule. The excluded measure is marked with "×" in **Table 40**. This approach avoids overlaps and potential double counting, while ensuring that the aggregated scenario reflects the highest reduction potential among mutually exclusive alternatives.

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WLC measure 5.2 was directly modelled for the 2030 and 2050 horizons. Accordingly, the directly modelled values were used for the 2030 and 2050 scenarios, while the 2040 value was estimated by linear interpolation between them.

WLC measure 5.3 was associated with the 2050 horizon but was excluded from the aggregated 2050 scenario because WLC measure 5.2 at the 2050 horizon was retained as the reference production-stage decarbonisation measure, due to its higher total WLC-GWP reduction potential.

WLC measure 8.2 was associated with the 2030 horizon but was not retained in the aggregated temporal scenarios because it overlaps with WLC measure 5.2 in the production-stage/material-related impact area. WLC measure 5.2 was retained as the reference measure across the 2030, 2040, and 2050 scenarios, using the directly modelled values for 2030 and 2050 and the interpolated value for 2040. WLC measure 8.2 was therefore excluded to avoid overlap and potential double counting.

For the **SFH typology**, Figure 65 presents the indicative aggregated reduction trajectory obtained for the SFH typology. The baseline WLC-GWP impact is normalised to an index value of 100, while the values reported for 2030, 2040 and 2050 represent the residual impact following the application of the retained WLC measures.

Based on this aggregation, the residual WLC-GWP impact decreases from 100 in the baseline scenario to 73 in **2030**, 65 in **2040** and 57 in **2050**, corresponding to total reductions of **27%**, **35%** and **43%**, respectively. The largest contribution is associated with WLC measure 5.2, for which the reduction increases across the temporal scenarios, with a directly modelled value for 2030, an interpolated value for 2040, and a directly modelled value for 2050. Measures 2.4.a, 2.4.b, 6.1, 6.2, 9.5, and 11.1 provide additional contributions that remain constant across the three temporal scenarios.

These values should be interpreted as indicative, scenario-based results derived from the compatibility and temporal-allocation assumptions described above.

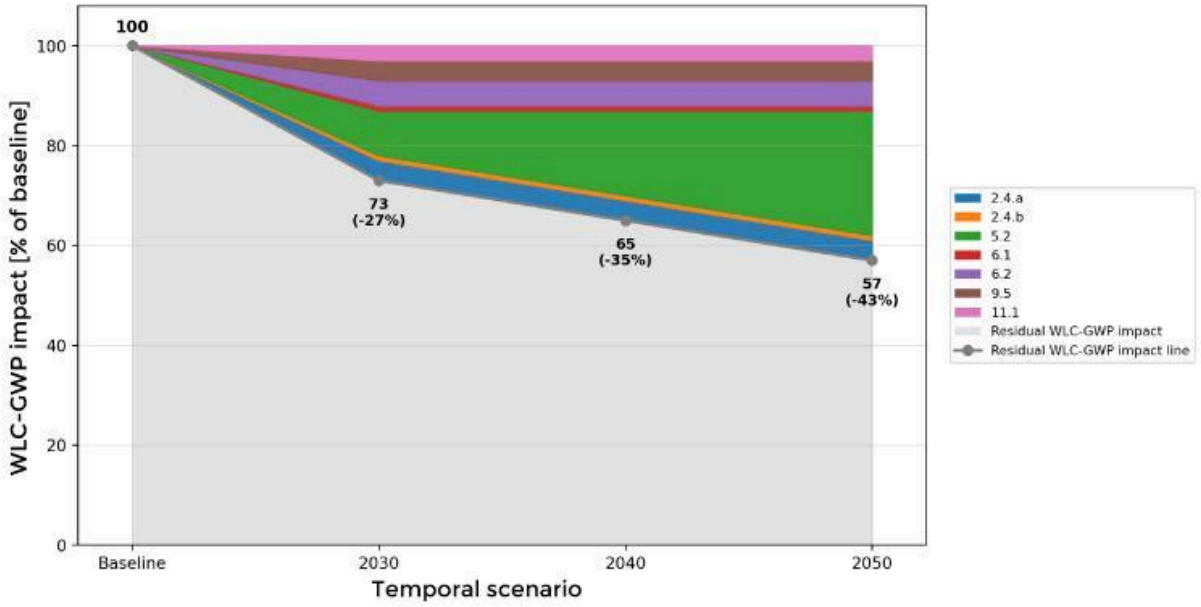


Figure 65. Aggregated WLC-GWP reduction trajectory for the SFH typology

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Regarding the **MFH typology**, Figure 66 presents the indicative aggregated WLC-GWP reduction trajectory obtained for the MFH typology.

According to this aggregation, the residual WLC-GWP impact decreases from 100 (assumed as a baseline example) to 69 in **2030**, 61 in **2040** and 54 in **2050**, corresponding to total reductions of **31%**, **39%** and **46%**, respectively. As for the SFH typology, the largest contribution is associated with WLC measure 5.2, which progressively increases its reduction potential over time. Compared with SFH, the MFH trajectory also shows a higher contribution from measure 9.5, reflecting the greater relevance of operational energy-related reductions in this typology. The remaining retained measures provide smaller and stable contributions across the temporal scenarios.

These values should be interpreted as indicative scenario-based results, derived from the compatibility and temporal allocation assumptions described above.

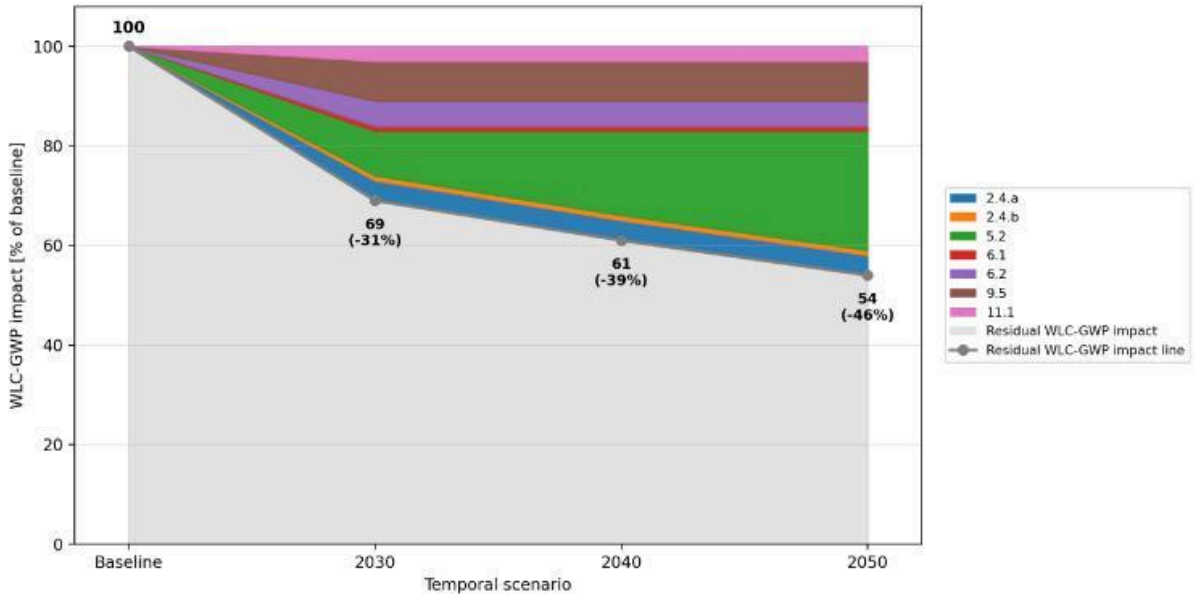


Figure 66. Aggregated WLC-GWP reduction trajectory for the MFH typology

In the case of the **OFF typology**, Figure 67 presents the indicative aggregated reduction trajectory obtained for the OFF typology. The baseline WLC-GWP impact is normalised to an index value of 100, while the values reported for 2030, 2040 and 2050 represent the residual impact after the application of the retained WLC measures.

According to this aggregation, the residual WLC-GWP impact decreases from 100 in the baseline scenario to 61 in **2030**, 52 in **2040** and 43 in **2050**, corresponding to total reductions of **39%**, **48%** and **57%**, respectively. The reduction trajectory is mainly driven by the combined contribution of WLC measure 5.2 and WLC measure 9.5. In particular, measure 9.5 provides a substantially higher contribution than in the residential typologies, reflecting the higher weight of operational energy-related impacts in office buildings. Measure 5.2 further increases the reduction potential towards 2050, while the other retained measures provide smaller and stable contributions.

These values should be interpreted as indicative scenario-based results, derived from the compatibility and temporal allocation assumptions described above.

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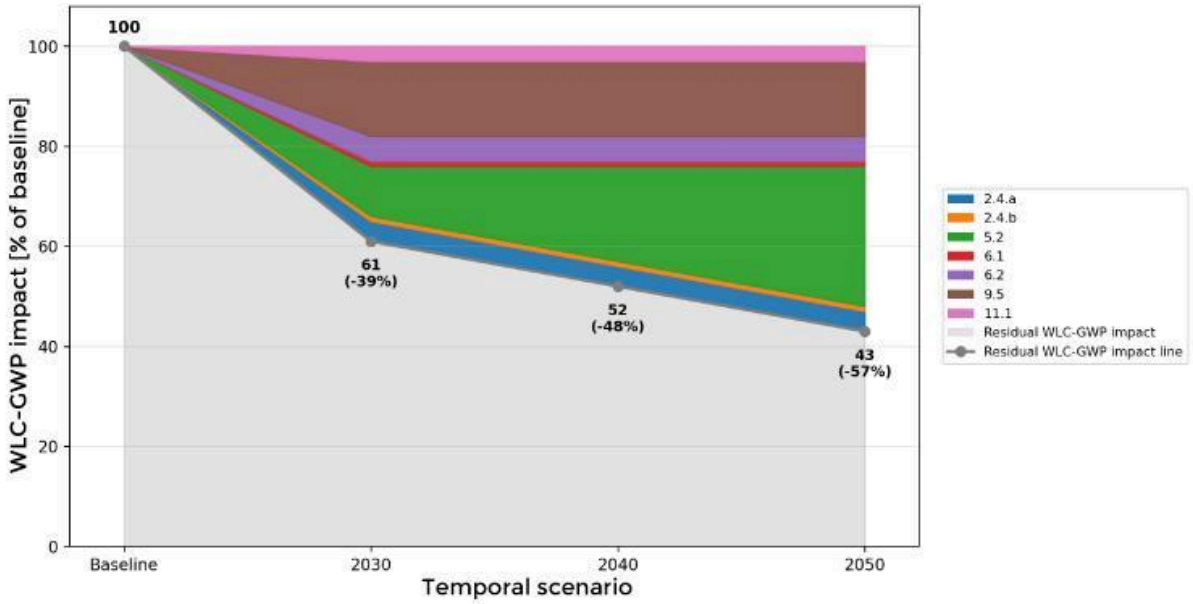


Figure 67. Aggregated WLC-GWP reduction trajectory for the OFF typology

As a final **comparison**, Figure 68 presents the indicative residual WLC-GWP trajectories obtained for the three analysed typologies. The baseline impact is normalised to an index value of 100 for all typologies, enabling a direct comparison of the relative reduction patterns across the temporal scenarios.

The comparison shows that the OFF typology achieves the strongest aggregated reduction, with total reductions of 39% in 2030, 48% in 2040 and 57% in 2050. MFH shows an intermediate trajectory, with reductions of 31%, 39% and 46%, respectively, while SFH records the lowest aggregated reduction, equal to 27% in 2030, 35% in 2040 and 43% in 2050. The stronger reduction observed for OFF is mainly related to the higher contribution of WLC measure 9.5, which reflects the greater relevance of operational energy-related impacts in this typology, together with the increasing contribution of WLC measure 5.2 over time.

The results confirm that the reduction potential of the aggregated scenarios is typology-dependent and is influenced by the relative weight of embodied and operational carbon in the baseline WLC profile.

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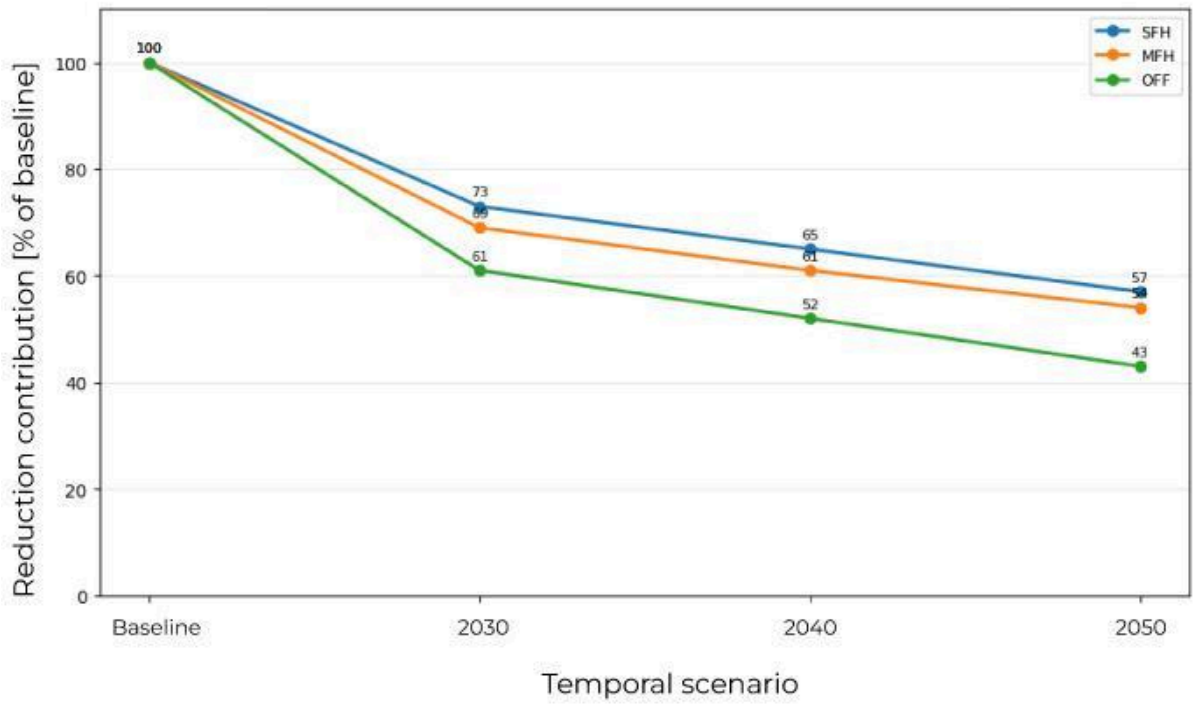


Figure 68. Indicative residual WLC-GWP impact trajectories for the SFH, MFH, and OFF typologies across the 2030, 2040, and 2050 temporal scenarios, with the baseline normalised to 100.

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8. Conclusions

In addressing the objective of report **D7.23**, dedicated to the definition of decarbonisation pathways and suitable design strategies for reducing **Whole Life Carbon** in the Italian building context, the analysis establishes an integrated methodological approach linking baseline results and hotspot analysis to the selection of WLC measures, their assessment across building typologies and the definition of indicative reduction targets.

Building upon the baseline results and hotspot analysis presented in D7.20, the study integrates the **ASI** framework with a cross-cutting interpretation based on the LCMs defined according to the **LCA** approach. This integration supports the development of a **WLC measures matrix** that systematises the analytical structure, identifies feasible actions within the scope of INDICATE LIFE, and supports the selection of specific measures for quantitative or qualitative assessment.

A key methodological contribution concerns the systematisation of WLC reduction strategies within a hierarchical structure composed of **pathways**, **strategy packages**, **WLC strategies** and **WLC measures**.

This structure made it possible to select, among the different potentially available strategies, those most consistent with the project scope, data availability and the possibility of being modelled in a traceable way on the Italian case studies. The measures were assessed through differentiated approaches, either quantitative or qualitative, depending on their relevance, data availability, technical feasibility of remodelling and consistency with the available datasets. On this basis, the evaluation highlights several key findings. First, WLC reduction requires an integrated and life-cycle-based approach, capable of combining measures acting on different stages of the building life cycle. The reduction potential is not uniform, but varies according to the measure considered, the module affected, the building typology and the temporal scenario adopted in the modelling.

A first finding concerns the central role of the production stage, represented by modules **A1-A3**. Among the measures assessed, this stage concentrates a relevant share of the reduction potential, confirming that material production and construction product supply chains remain critical areas for WLC decarbonisation. Measures addressing the decarbonisation of production processes, the use of materials with higher recycled content and the application of CO_2 capture technologies show relevant effects in this stage. However, their contribution varies depending on the construction system, material composition and scenario assumptions adopted in the 2030 and 2050 scenarios.

The use stage, and in particular module **B6**, shows a more typology-dependent behaviour. Office buildings are more sensitive to measures reducing operational emissions, due to the higher weight of **Operational Carbon** in the baseline. By contrast, residential typologies remain predominantly characterised by **Embodied Carbon**, even after the application of operational energy decarbonisation measures.

These findings support the conclusion that WLC reduction priorities should not be applied uniformly across building categories, but should instead be defined in relation to the specific carbon profile of each typology. The assessment also shows that modules related to transport, construction processes and end-of-life stages generally produce lower absolute reductions. This is consistent with their lower contribution to the baseline WLC profile. However, these stages remain relevant within integrated decarbonisation scenarios, especially when combined with measures acting on material production, operational energy and replacement cycles.

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Their lower absolute contribution should therefore be interpreted in relation to the reduction potential available within these life-cycle stages.

When results are aggregated according to the **ASI** framework, the **Improve** pathway shows the highest quantified reduction among the modelled measures.

This result should not be interpreted as evidence of an intrinsic superiority of Improve over Avoid or Shift, but rather as reflecting differences in methodological maturity, data availability and modelling feasibility across the three pathways. The Avoid pathway also provides a significant contribution, particularly through measures related to durability, maintenance and circular material use. The Shift pathway was not quantitatively assessed, due to methodological constraints associated with the direct substitution of conventional materials with bio-based alternatives in the available case studies.

The analysis of measure combinations confirms that WLC reduction cannot always be calculated as the simple sum of the benefits of individual measures. Interactions between measures may generate synergies, overlaps or possible double-counting effects. The compatibility matrix therefore represents a necessary step for identifying technically and methodologically consistent combinations. The combined application of selected measures indicates an overall reduction potential of **27%** for **SFH**, **25%** for **MFH** and **31%** for **OFF**, showing that the **effectiveness of integrated decarbonisation scenarios** depends on the **compatibility and interaction among the measures considered**, rather than on the simple addition of their individual effects.

The target values proposed should therefore be understood as indicative reduction values relative to the baseline. They do not represent regulatory thresholds or directly applicable limit values, but rather evidence-based references derived from the assessed case studies and the modelling assumptions adopted. Their main value lies in identifying plausible reduction orders of magnitude, priority life-cycle stages and compatible combinations of measures that can support future WLC target-setting processes.

Overall, the evaluation highlights that effective WLC decarbonisation in the Italian building context requires a differentiated, life-cycle-based and typology-sensitive approach. The methodological approach developed provides a structured link between baseline hotspots, decarbonisation measures, their compatibility and measurable reduction targets, and can support future benchmarking activities, progressive reduction trajectories, and policy, procurement or voluntary certification tools aimed at reducing **WLC** in the building sector.

8.1. Limitations, uncertainties and future developments

The target values proposed should be interpreted with caution, as they are derived from **scenario-based** modelling and depend on the assumptions adopted throughout the assessment process. The results reflect the methodological framework developed within **INDICATE LIFE IT**, the characteristics of the analysed case studies, and the availability, **representativeness** and quality of the underlying data.

In particular, several aspects may influence the robustness and transferability of the proposed targets:

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- **Representativeness of the case studies.** The case studies used for the remodelling represent a selected subset of the **INDICATE LIFE IT** sample. Although the selection process was designed to balance impact intensity, construction representativeness, data quality and modelling feasibility, the results cannot be considered statistically representative of the entire national building stock. They should therefore be interpreted as outcomes derived from selected and methodologically controlled case studies, rather than as values directly generalisable to the whole Italian building stock. Future validation should extend the assessment to a broader and more diversified sample in order to test the **robustness** and **transferability** of the proposed reduction values.

- **Dependence on future scenarios.** A further source of uncertainty concerns measures that depend on future scenarios of technological development, market penetration and regulatory implementation. This is particularly relevant for the decarbonisation of production processes, the diffusion of renewable energy sources in industrial production, carbon capture and storage technologies, the decarbonisation of transport, and the increased availability of recycled material flows. In these cases, the results should be interpreted as **scenario-based** estimates rather than deterministic forecasts. Subsequent updates should therefore incorporate revised technological, market and regulatory assumptions as more robust evidence becomes available, allowing the reduction trajectories to be progressively refined.

- **Representativeness and granularity of environmental datasets.** An additional aspect to consider concerns the level of representativeness and granularity of the environmental datasets used to build the baseline. These datasets may present different levels of detail and different degrees of geographical and technological representativeness with respect to the production conditions of the Italian context. This aspect may influence both the interpretation of the baseline results and the estimation of the reduction potential of the remodelling scenarios, particularly for measures addressing material substitution, increased recycled content or the decarbonisation of production processes. The results should therefore be interpreted by considering the degree of **representativeness** and **granularity** of the environmental datasets used in relation to the context of application.

- **Data quality and methodological harmonisation.** Differences in data quality, completeness and consistency may affect the robustness of the calculated reductions, particularly when alternative scenarios are compared using datasets developed from heterogeneous sources. More systematic data-quality checks and harmonisation procedures would improve the consistency and comparability of environmental information across materials, processes and scenarios. Particular attention should also be paid to methodological consistency when combining environmental data from different sources, including the methods and characterisation factors applied, with reference to the relevant requirements of EN 15804.

The assessment should also be extended to a wider and more diversified set of case studies, in order to test the robustness of the results and identify possible correlations between WLC reductions, construction typologies, climatic zones, seismic zones and building geometry. The quantitative assessment should also cover measures and pathways that could not be modelled within the present analysis, particularly the Shift pathway, in order to improve the balance and completeness of the ASI-based assessment. Additional analyses could focus on retrofit interventions, which are

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particularly relevant in the Italian context and may already constitute, by their nature, a strategy for reducing impacts compared with new construction.

Overall, the methodological approach developed provides a structured link between decarbonisation strategies, design measures and measurable WLC reduction values at building scale. Despite the limitations outlined above, the results make it possible to identify the life-cycle stages and intervention categories with the highest reduction potential, while also defining the areas where broader case-study coverage, stronger data quality and more robust scenario development are required. These elements can contribute to the progressive definition of science-based national targets for reducing the Whole Life Carbon of buildings in Italy.

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UNIBG coordinated the methodological development of the deliverable, including the definition of the overall analytical structure, the development of a matrix linking the ASI framework with the life-cycle modules, the operational approach for the modelling of WLC measures, and the procedures for case-study selection, result integration and target definition.
Quantitative remodelling activities were distributed among the research units according to the selected WLC measures and representative case studies. Across the eight WLC measures assessed quantitatively, UNIBG contributed to all 8 measures, POLITO to 4 measures, and POLIMI to 2 measures, including measures jointly assessed by more than one research unit.
The processing, integration and interpretation of the results were led by UNIBG as task leader. UNIBG also developed and coordinated the methodological approach for assessing the combined effects of multiple WLC measures and the temporal decarbonisation scenarios.

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Specific contribution

Section 5.2.2 was prepared by Dr Martina Vitali as part of her research fellowship activities. The content was subsequently reviewed and integrated by the coordinators of this deliverable.

Declaration of AI-assisted language editing

During the preparation of this deliverable, generative AI tools were used to support the revision of the English language. The authors reviewed and edited the text as necessary and remain fully responsible for the content of this deliverable.

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