ARV

CLIMATE POSITIVE CIRCULAR COMMUNITIES

REPORT ON STREAMLINED LCA-LCCA COMPARING ALTERNATIVE SOLUTIONS AND SCENARIOS

WORK PACKAGE 8

Gianluca Grazieschi, Patricia Schneider-Marin, Iuliia Maskova, Antoni Llabrés Payeras, David Mayol Laverde, Rossano Albatici, Gianluca Maracchini, Alessandro Prada, Nicola Callegaro, Nicola Lolli, Kristian Stenerud Skeie, Sara A. Sharbaf, Eirik Resch, Robert Wawerka, Licia Felicioni, Nikola Pokorny, Emma Koster, Karin Grooten, Martin van Dijkhuizen, Rogier Laterveer, Adriano Bisello, Daniele Vettorato, Irene Bertolami.

30/01/2024

This project has received funding from the European Union’s Horizon 2020
research and innovation programme under grant agreement No 101036723

PROJECT INFORMATION

Project acronym	**ARV**[1]
Project title	Climate Positive Circular Communities
Project number	101036723
Coordinator	Norwegian University of Science and Technology / Inger Andresen
Website	www.GreenDeal-ARV.eu

DOCUMENT INFORMATION

Deliverable Number and Title	**D.8.5 Report on streamlined LCA-LCCA comparing alternative solutions and scenarios**
Due Month	Month 25 (January 2024)
Work Package Number and Title	WP 8. Monitoring, evaluation and impact assessment
Task number and Title	Task 8.4. Assessment of environmental, social, and economic impacts
Dissemination Level	PU = Public, fully open
Date of Delivery	30.01.2024
Lead Author	Gianluca Grazieschi (EURAC)
Contributors	Iuliia Maskova (IREC) Antoni Llabrés Payeras (PALMA) David Mayol Laverde (IBAVI) Rossano Albatici (UNITN) Nicola Callegaro (UNITN) Gianluca Maracchini (UNITN) Alessandro Prada (UNITN) Licia Felicioni (CVUT) Nikola Pokorny (CVUT) Robert Wawerka (CVUT) Emma Koster (UAS) Karin Grooten (UAS) Martin van Dijkhuizen (UAS) Rogier Laterveer (UAS) Patricia Schneider-Marin (NTNU)

---

[1] *ARV is a Norwegian word meaning "heritage" or "legacy". It reflects the emphasis on circularity, a key aspect in reaching the project's main goal of boosting the building renovation rate in Europe.*

	Sara A. Sharbaf (NTNU) Eirik Resch (NTNU) Nicola Lolli (SINTEF) Kristian Stenerud Skeie (SINTEF) Adriano Bisello (EURAC) Irene Bertolami (EURAC) Daniele Vettorato (EURAC)			
Reviewers	David Mayol Laverde (IBAVI)			
Status	Draft			
Revision Log	Version	Author	Main changes	Date
	V.01	Gianluca Grazieschi et al.	First draft	20.04.23
	V.02	Gianluca Grazieschi, David M. Laverde	Second draft after internal review	10.12.22
	V.03	Gianluca Grazieschi, Patricia Schneider-Marin et al.	Version ready for quality review	10.01.2024
	V.04	David M. Laverde, Inger Andresen et al.	Version after quality review	15.01.2024
	V.05	Gianluca Grazieschi	Final version	29.01.2024

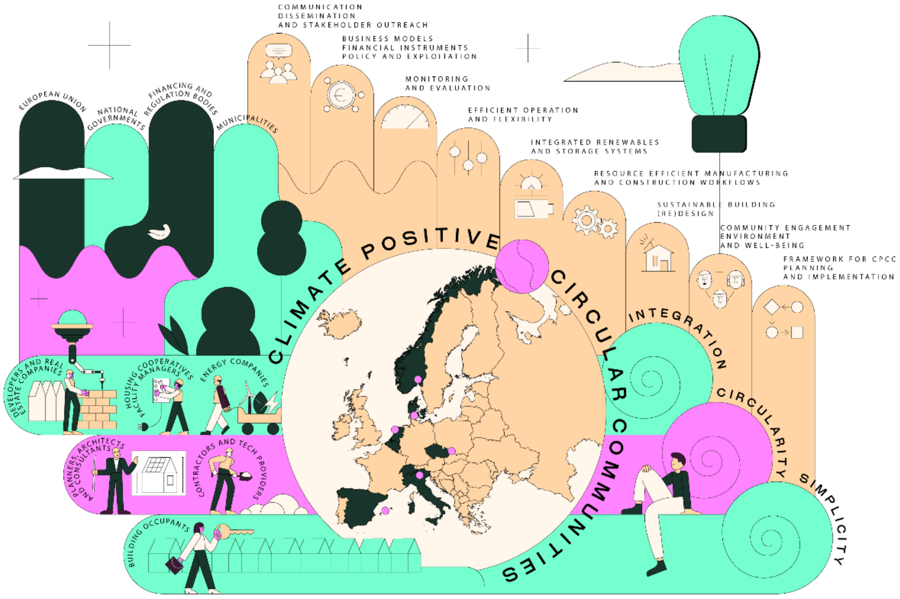
ABOUT THE ARV PROJECT

The vision of the ARV project is to contribute to a speedy and wide scale implementation of Climate Positive Circular Communities (CPCC) where people can thrive and prosper for generations to come. The overall aim is to demonstrate and validate attractive, resilient, and affordable solutions for CPCC that will significantly speed up the deep energy renovations and the deployment of energy and climate measures in the construction and energy industries. To achieve this, the ARV project will employ a novel concept relying on a combination of 3 conceptual pillars, 6 demonstration projects, and 9 thematic focus areas.

The 3 conceptual pillars are integration, circularity, and simplicity. **Integration** in ARV means the coupling of people, buildings, and energy systems, through multi-stakeholder co-creation and the use of innovative digital tools. **Circularity** in ARV means a systematic way of addressing circular economy through an integrated use of Life Cycle Assessment, digital logbooks, and material banks. **Simplicity** in ARV means to make the solutions easy to understand and use for all stakeholders, from manufacturers to end-users.

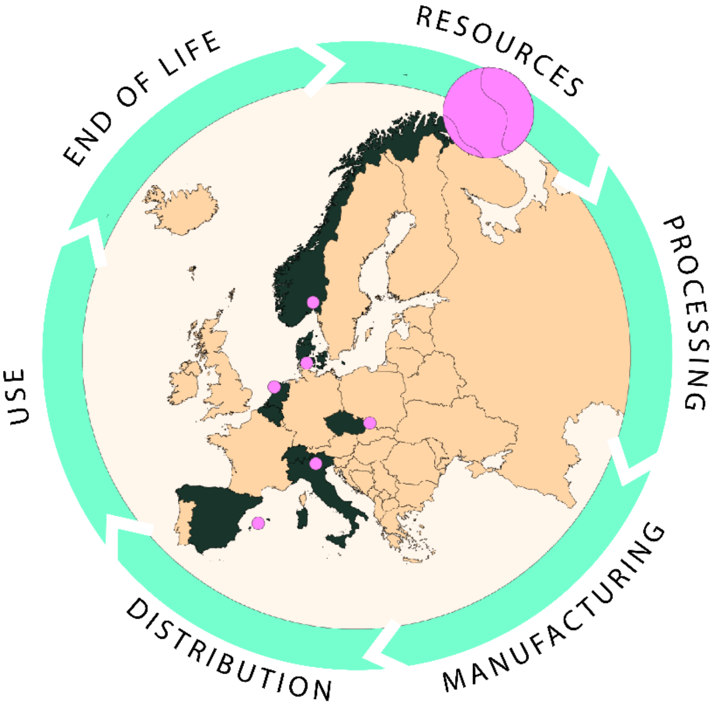
The 6 demonstration projects are urban regeneration projects in 6 locations around Europe. They have been carefully selected to represent the different European climates and contexts, and due to their high ambitions in environmental, social, and economic sustainability. The Renovation of social housing and public buildings is specifically focused. Together, they will demonstrate more than 50 innovations in more than 150,000 m^2 of buildings.

The 9 thematic focus areas are 1) Effective planning and implementation of CPCCs, 2) Enhancing citizen engagement, environment, and well-being, 3) Sustainable building re(design) 4) Resource efficient manufacturing and construction workflows, 5) Smart integration of renewables and storage systems, 6) Effective management of energy and flexibility, 7) Continuous monitoring and evaluation, 8) New business models and financial mechanisms, policy instruments and exploitation, and 9) Effective communication, dissemination, and stakeholder outreach.



The ARV project is an Innovation Action that has received funding under the Green Deal Call LC-GD-4-1-2020 - Building and renovating in an energy and resource efficient way. The project started in January 2022 and has a project period of 4 years, until December 2025. The project is coordinated by the Norwegian University of Science and Technology and involves 35 partners from 8 different European Countries.

EXECUTIVE SUMMARY



This Deliverable tries to set up a streamlined LCA-LCC assessment methodology specifically oriented to support and inform the designers of the ARV interventions in selecting sustainable solutions. This effort tries to overcome the limitation of the traditional methodologies to evaluate the sustainability of building interventions that are focusing only on improving energy efficiency or containing the initial investment. In the first case, in fact, the burdens associated with additional materials used to accomplish energy efficiency are not usually considered. On the contrary, in the latter, the only minimization of investment costs could result in a building with a low energy performance and thus with very high operational costs. The adoption of a life cycle approach, with "cradle-to-cradle" perspective, was recognized as the only one that was able to detect burden shifting and trade-off between different life cycle stages providing a comprehensive economic and environmental assessment.

The adoption of a life cycle approach is supported by the ARV project, the expected impact of which foresees specific targets in relation to primary energy savings, life cycle emissions savings, embodied energy reductions or circular economy. To verify that the design of the interventions implemented in ARV was on the right path to achieve the expected impacts, all the main stakeholders and experts working on sustainability assessment were involved in the application of simplified LCA-LCC methodologies.

The main difficulties encountered in applying LCA-LCC methodologies during the early design stage were related to the time consumed in collecting input data, to the lack of experience, to the high cost for software licences and to the difficulty in integrating data within different tools.

A continuous discussion was undertaken to define the main working hypotheses to streamline the LCA-LCC methodologies without loosing their efficacy in assessing different scenarios during the early design stage. It was demonstrated that opting for few impact indicators (i.e., the most well-established and consolidated ones like the cumulative primary energy demand and the Global Warming Potential) along with few attributes for comparing preliminary scenarios, robust sustainability decisions can be made in early-design stages, thereby promoting a reduction in environmental impacts and costs.

The applications put forth by the groups working on various demonstration projects demonstrated that the implemented design strategies and ambitions can yield outcomes consistent with the anticipated impacts of the project. Significant environmental benefits could be achieved in relation to primary energy saving and GHG emissions reduction. The achievement of cost benefits in the life cycle resulted instead more challenging, particularly if excluding incentives.

The validation of the expected performances presented in this report using actual monitored data will be the subject of the forthcoming deliverables within work package 8.

TABLE OF CONTENTS

1. INTRODUCTION

The current European policies emphasize the improvement of energy efficiency and of the renewable energy integration in buildings.

According to the recast of the Directive EPBD (Energy Performance of Buildings Directive), Member States should target nearly zero energy buildings (NZEBs) and cost-effective minimum energy performance standards starting from 2020.

The pathway that is followed to achieve the **NZEB target** is usually based on the following steps:

1. Reduction of the operational energy consumptions of the buildings acting on their air tightness and on the thermal transmittance of envelope components;
2. Increase of the efficiency of energy and ventilation systems;
3. Use of low temperature waste heat or electrification of the building sector (e.g., through heat pumps);
4. Introduction of decentralized renewable energy production systems (e.g., PV or solar thermal systems).

The improvement of the operational energy performance of the buildings is generally followed by an increase in their embodied environmental impacts and costs, linked to the necessity of introducing new envelope components and energy systems (e.g., insulation materials, photovoltaic plants, geothermal probes, etc.). In particular, for highly energy-efficient buildings the embodied components can account for more than a half of the total life cycle burden (Röck et al., 2020).

Even if this **burden shifting** onto the upstream life cycle stages of the buildings is generally beneficial in the life cycle perspective, it should be evaluated during the design stage because, in some cases, it can result in a worsening of the overall environmental and economic performances of the constructions. That is why the application of life cycle methodologies in the selection of design solutions is strongly recommended.

Moreover, when embodied impacts acquire a significant role in determining the overall environmental performance of a building, the implementation of design strategies able to **minimize the trade-off** on upstream life cycle stages becomes a further step that can generate environmental or cost savings. In this field, different strategies can be considered, e.g. the selection of low-energy/carbon intensive materials, the reuse of waste materials, the selection of materials with a high recycled content, the application of circular economy principles in general, the design of the end-of-life of the building materials aiming at enhancing their reuse and recycle potential, the prefabrication of building components to avoid construction waste or to optimize material use. The ARV project pursues this goal, aiming at reducing the embodied energy and the life cycle costs of interventions proposed if compared to the current local practices.

Considering this background, the Deliverable 8.5 of the ARV project presents the methodologies that were applied in the demo cases in order to contain the unavoidable trade-off on embodied impacts that characterizes the life cycle environmental and cost performance of low-energy buildings or retrofits in the local practice.
They basically consist in the application of streamlined Life Cycle Assessment (**LCA**) and Life Cycle Costs (**LCC**) methods during the preliminary design phase to support the selection of solutions that are able to optimize the overall environmental and economic performance of the ARV interventions.

2. EUROPEAN LEGISLATION AND INITIATIVES

Starting from the new millennial, the growing attention to the topic of energy performance of the building sector in Europe, is witnessed by the issuance of Directive 2002/91/CE. This directive provided a common framework for all member states, outlining guidelines for methodological approaches, limits to be enforced, and deadlines for implementing national legislations in alignment with its provisions.
The subsequent Directive 2010/31/CE, known as the **Energy Performance of Buildings Directive Recast** (EPBD recast), represents an evolution of Directive 2002/91/CE. EPBD recast addresses several key aspects, which include:

1. Methodology for the calculation of energy performances in buildings
2. System for the certification of the energy performances
3. Setting of the minimum energy performance requirements
4. Control system and independent experts
5. NZEBs (Nearly Zero Energy Buildings)

Similar to the previous Directive, the EPBD recast primarily focuses on the energy performance in buildings. However, it introduces two significant aspects within the construction sector framework: the establishment of cost-optimal levels for calculating minimum energy requirements and the definition of nearly Zero Energy Buildings (NZEBs).

Article 2.2 of the Directive defines NZEB as "*a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including energy from renewable sources produced on-site or nearby*".

Furthermore, in addition to providing a definition, the EPBD stipulates that all new private and public buildings must meet the NZEB standard by December 31st, 2020, and December 31st, 2018, respectively. It's important to note that the EPBD does not provide specific quantitative benchmarks for defining NZEBs. Instead, this task is delegated to the member states, which are responsible for establishing their minimum energy requirements and implementing appropriate policies to promote NZEBs.

Article 5 of the Directive, on the other hand, lays out a comparative methodological framework for determining the optimal levels of minimum energy performance in buildings based on cost considerations.

The Commission Delegated Regulation number 244, dated January 16, 2012, provides a more in-depth explanation of this general framework. It establishes a standardized methodology for identifying a local minimum in the cost function relative to the primary energy demand of buildings. This approach allows EU member states the flexibility to establish their own national benchmarks against which minimum energy requirements can be defined.

The amendment of the EPBD Recast in June 2018 **(EPBD Recast 2018/844/EU)** proposed specific modifications to the 2010 version designed to accelerate the cost-effective refurbishment of the existing buildings, envisioning a carbon-neutral building stock by 2050. The amendment also encouraged the installation of electric vehicle charging infrastructures in building parking areas and introduced new provisions to improve intelligent technologies and technical building systems, including automation.

The **Energy Efficiency Directive** (EED) is a pivotal piece of legislation within the European Union that plays a fundamental role in shaping and advancing energy efficiency measures across member states. Enacted in 2012 and amended in 2018, the EED provides a comprehensive framework for achieving significant energy savings, reducing greenhouse gas emissions, and enhancing energy security.

The Energy Efficiency Directive incorporates a range of provisions aimed at fostering energy efficiency in various sectors, including buildings, industry, and transportation.
The first version, represented by Directive 2012/27/EU, establishes a legislative framework designed to assist member states in enacting national laws aimed at achieving a 20% reduction in the primary energy consumption by 2020. The EED underwent an amendment in 2018 (2018/2002/EU) to establish a legal framework for the 2030 energy efficiency targets and prolong the applicability of article 7 until 2030. The amendment introduced an even more ambitious target of at least 32.5% energy efficiency improvement by 2030 (relative to the 2007 reference scenario).

Given that buildings account for a significant portion of primary energy consumption in Europe, the EED places a strong emphasis on improving the energy efficiency of public buildings. Article 5 of the EED mandates that, starting from the first of January 2014, and for each subsequent year, member states must undertake retrofitting measures for at least 3% of the total floor area of existing public buildings, ensuring they meet minimum energy performance requirements. This requirement serves as a crucial component of efforts to enhance energy efficiency and reduce energy consumption in the building sector.

Articles 8 to 12 of the directive focus on auditing and metering practices to promote a better energy management. These measures encourage energy consumers to improve their consumption habits by providing easy and free access to consumption data and individual metering. Additionally, they incentivize small and medium enterprises to conduct energy audits, while large companies are compelled to undergo audits to identify the best strategies for reducing energy use.

Article 7, titled "Energy Efficiency Obligation Schemes," is a pivotal aspect of the Directive. It mandates that energy distributors or retail energy sales companies must implement energy efficiency obligations and/or alternative policy instruments aimed at achieving a yearly reduction of 1.5% in final energy use. This requirement plays a crucial role in advancing energy efficiency initiatives and reducing overall energy consumption.

The implementation of the EED has faced several challenges. Achieving the ambitious energy efficiency targets necessitates significant investments in energy-saving technologies, changes in consumers' behaviour, and regulatory adjustments. Member states vary in their progress toward meeting these targets, which has led to disparities in energy efficiency efforts across the EU (Economidou et al., 2020).

Despite challenges, the EED has made notable contributions to energy efficiency in the EU. It has spurred energy-saving measures in various sectors, leading to reduced energy consumptions, lower greenhouse gas emissions, and enhanced energy security. Additionally, it has created opportunities for businesses specializing in energy efficiency technologies and services. Its impact extends beyond energy savings, encompassing economic growth, job creation, and environmental benefits. As the EU continues to advance its climate and energy ambitions, the EED is poised to play an even more pivotal role in shaping the energy landscape of Eu countries and contributing to global efforts to contain climate change.

The **Renewable Energy Directive** (RED - EU, 2009/28/EU) aims at fostering the adoption of renewable energy sources across European member states. This directive outlines binding targets for the share of renewable energy in the EU final energy consumption. This includes targets for the overall share of renewables in the energy mix, as well as specific targets for the use of renewables in various sectors, such as electricity, heating and cooling, and transport; specific objectives and deadlines are allocated to each country.
The member states of the EU are required to develop National Renewable Energy Action Plans outlining how they intend to meet their individual renewable energy targets. These plans serve as a roadmap for the renewable energy development of each member state.

The RED encourages member states to implement support schemes to incentivize the production and use of renewable energy. These support mechanisms can include feed-in tariffs, investment grants, tax incentives, and renewable energy certificates. The directive establishes a system of Guarantees of Origin to track and certify the origin of renewable energy. This mechanism provides transparency and allows consumers to make informed choices about the renewable energy they use.
Additionally, the RED Directive introduces flexibility through three cooperation mechanisms designed to assist member states in achieving their predetermined targets: statistical transfer, joint projects, and joint support schemes. Statistical transfer involves the virtual transfer of renewable energy among the member states; joint projects entail collaborative renewable energy initiatives between two or more nations; joint support schemes enable the combination of various support mechanisms to reach national renewable energy targets.
Here are the main aspects of the RED related to the building sector:

- The RED sets specific targets for the share of renewable energy in the heating and cooling of buildings. Member states are required to establish indicative national targets for increasing the use of renewable energy in this sector.
- The directive encourages the use of renewable energy sources (e.g., solar thermal, biomass, and geothermal) in district heating and cooling systems, which serve multiple buildings or even entire communities.
- The RED recognizes the importance of energy efficiency in buildings. It encourages member states to implement measures to improve the energy performance of buildings alongside increasing the use of renewable energy. This includes the installation of solar panels, heat pumps, and other technologies that generate renewable energy for on-site use.

Alongside with the directive, the EU has already launched different initiatives and instruments to support the renovation of the building stock and the construction of NZEBs.

The **European Green Deal** is a comprehensive strategy introduced in 2019 with the goal of making the EU climate-neutral by 2050. It includes various initiatives related to buildings, such as the **Renovation Wave**, which aims to double the renovation rate of existing buildings by 2030. Energy efficiency is a core focus of the Green Deal in the building sector alongside with the promotion of NZEBs. Moreover, the EU Green Deal encourages a circular economy approach in construction and renovation and promotes the digitalization of the building sector through smart technologies, such as building automation systems, sensors, and energy management platforms, as a way to optimize energy use, enhance occupant comfort, and reduce emissions.

Energy Performance Contracts (EPCs) are other instruments that are deployed by the EU to foster energy efficiency in buildings. They consist of agreements between an energy service company (ESCO) and a client, typically a public or private organization, aimed at improving energy efficiency and reducing energy consumption in buildings or facilities.

Cohesion Policy Funds can also play a significant role in supporting building stock renovation, particularly in regions with economic and social disparities.

2. LITERATURE REVIEW

2.1. NZEB DEFINTION

As previously mentioned, there is not a standardized international definition for a NZEB. This section aims at outlining the main aspects that need to be clarified to establish a scientifically sound definition of a NZEB building.

2.1.1. PHYSICAL BOUNDARIES

The boundaries of the system for NZEBs can vary considerably. Energy production systems, for example, may be located on-site or off-site. Typically, the building footprint or the property lines of the building are considered as the system boundaries. However, there are exceptions. For instance, in the case of UK zero carbon homes, investments in low-carbon projects outside the physical boundaries of the building can also be considered for the calculation of the NZEB balance. This might involve investments in local energy infrastructures or funding energy retrofits for buildings in the surrounding area to contribute to achieve the NZEB balance.

2.1.2. BALANCING BOUNDARIES

The balancing boundary conditions, on the other hand, specify which energy uses should be taken into account. Typically, operational energy uses encompass heating, cooling, ventilation, domestic hot water, lighting, and domestic appliances.
Conversely, energy uses that are typically not considered in the NZEB balance include embodied energy/emissions in materials and technical installations.

2.1.3. OTHER SPECIFICATIONS

Defining boundary conditions is crucial, and it involves specifying factors such as the function of the spaces, the density of people within those spaces, external climatic conditions, and internal comfort requirements. A change in the use of the building, such as a transition from residential to commercial, can lead to an energy imbalance due to variations in energy requirements as well as in people density. It's also essential to clearly define reference values for external climate conditions and internal comfort standards.

2.1.4. CONVERSION/WEIGHTING FACTORS

Conversion factors are useful to standardize the measurements of various energy vectors, allowing for a uniform metric. This metric, for instance, can encompass the entire energy chain from the extraction of natural resources to conversion processes, transmission, and distribution networks. Utilizing a single unit of measurement also enables the consideration of the "fuel switching effect": it accounts for the compensation during the summer when electricity generated by a photovoltaic plant offsets electricity imported during the winter.

Commonly used types of units include local/primary energy use, energy costs, carbon emissions from energy use, non-renewable primary energy, or exergy. The choice of conversion factors, particularly if strategic, can favour certain energy carriers over others and influence the required generation capacity. It's important to note that there are not universally correct conversion factors. Instead, different values are possible depending on the purposes of the analysis and underlying assumptions. Political factors can also come into play, either promoting or discouraging specific energy sources. For example,

adopting carbon emissions as a fundamental unit of measure may incentivize the development of biomass plants.
Energy vectors can be weighted symmetrically or asymmetrically when calculating their contribution to the NZEB balance.

In a symmetric approach, the same conversion factor is used for both input and output energy flows. This method assumes that the energy exported/generated offsets the equivalent amount of energy that would have been generated elsewhere. Conversely, an asymmetric weighting assigns different conversion factors to energy demand and supply. This reflects the idea that energy demand and supply may not have equal value or impact.
Basically, two approaches can be considered:

- Higher conversion factors are assigned to imported energy. This is done to account for the costs and losses incurred during the transport and storage of energy within the network. By applying higher conversion factors, the method seeks to discourage reliance on energy imported from the grid and encourage greater self-consumption within the building. This approach recognizes that energy losses and inefficiencies are associated with the distribution and transmission of energy through the network, making imported energy less desirable from an environmental and economic standpoint.
- Exported energy is weighted by a higher factor. This strategy is intended to incentivize the use and deployment of specific technologies in an environment where they are expected to grow. For example, during the initial stages of the diffusion of photovoltaic technology in Italy, the energy produced by photovoltaic systems was compensated at a rate two or three times higher than the cost of conventionally delivered energy to the building [ref]. This asymmetrical pricing, favouring energy generated by photovoltaics, was designed to encourage the adoption of solar power generation systems and stimulate their growth in the energy market. It provided an economic incentive for property owners to invest in photovoltaic installations, helping to expand the use of this renewable energy source.

2.1.5. CALCULATION METHODOLOGIES

The calculation of the energy balance in NZEBs can be approached in various ways, and the choice of the method to be applied often depends on the desired level of detail required. Typically, the time period used for these calculations is annual, but there are considerations for both shorter and longer timeframes. The following points resume the possible approaches that could be adopted.

1. **Annual Calculation**: this is the most common approach. It involves assessing energy generation and consumption over the course of a year, considering seasonal variations in weather and energy use. An annual calculation provides a balanced view of energy flows and allows for the design of systems that can meet the building energy needs throughout the year.
2. **Shorter Calculation Periods (e.g., monthly or seasonal)**: while annual calculations are useful, they can sometimes result in not very strict design requirements, especially in regions with extreme weather variations. Shorter calculation periods, such as monthly or seasonal, can be used to analyse energy balance with a higher level of granularity. This approach helps in designing systems that perform optimally during specific seasons or months.
3. **Longer Calculation Periods (e.g., decades)**: in some cases, it may be beneficial to consider the entire life cycle of a building, which could span several decades. This long-term perspective is valuable for assessing the building sustainability and resilience over time. However, this may require a very long monitoring period or assumptions regarding future energy trends and technological advancements.

The choice of the calculation period depends on the project objectives, the availability of data, and the desire for precision. Shorter periods may be preferred for optimizing system design, while longer periods may be more suitable for evaluating the building performance over its entire lifespan.
The following formulas present two different calculation methodologies for assessing the energy balance in NZEBs.

Balance between weighted demand and weighted supply

$$\sum_{\mathbf{i}} \int \mathbf{P}_{\mathbf{exp,i}}(\mathbf{t}) \cdot \mathbf{w}_{\mathbf{exp,i}}(\mathbf{t}) \cdot \mathbf{dt} - \sum_{\mathbf{i}} \int \mathbf{P}_{\mathbf{del,i}}(\mathbf{t}) \cdot \mathbf{w}_{\mathbf{del,i}}(\mathbf{t}) \cdot \mathbf{dt} = \sum_{\mathbf{i}} \mathbf{E}_{\mathbf{p,exp,i}} - \sum_{\mathbf{i}} \mathbf{E}_{\mathbf{p,del,i}} \geq 0$$

$\mathbf{E}_{\mathbf{p,nren,U}}$ - the primary energy in the use stage [kWh/m^{2}y];

$\mathbf{E}_{\mathbf{p,nren,del,i}}$ - delivered primary energy per energy carrier ***i*** [kWh/m^{2}y];

$\mathbf{E}_{\mathbf{p,nren,exp,i}}$- exported primary energy per energy carrier ***i*** [kWh/m^{2}y];

$\mathbf{P}_{\mathbf{del,i_i}}$ - the delivered power on site or nearby for energy carrier ***i*** [kW/m^2];

$\mathbf{w}_{\mathbf{del,nren,i}}$ - the primary energy factor for the delivered energy for energy carrier ***i*** [-];

$\mathbf{P}_{\mathbf{exp,i}}$ - the exported power on site or nearby for energy carrier ***i*** [kW/m^2];

$\mathbf{w}_{\mathbf{exp,nren,i}}$ - the primary energy factor of the exported energy for energy carrier ***i*** [-].

Balance between load and generation of energy

$$\sum \boldsymbol{g_i\, w_{g,i}} - \sum \boldsymbol{l_i\, w_{l,i}} = \boldsymbol{G_P} - \boldsymbol{L_P} \geq \mathbf{0}$$

$\boldsymbol{g_i}$ is the energy generated for energy carrier ***i*;**

$\boldsymbol{l_i}$ is the energy load for energy carrier ***i*** ;

$\boldsymbol{w_{g,i}}$ is the primary energy conversion factor for the energy generation carrier ***i*;**

$\boldsymbol{w_{l,i}}$ is the primary energy conversion factor for the energy load carrier ***i*.**

The primary distinction between the two balancing types lies in the availability of detailed estimations of the self-consumption during the design of the NZEB.
In the first case, where a detailed estimation of the "self-consumption" is required, it is essential to have access to comprehensive data about the building energy loads, particularly with a sufficient level of time resolution. This means that data about how and when energy is consumed within the building must be available during the design phase. This detailed information is crucial for accurately assessing how much of the renewable energy generated by the building is immediately used by the building itself. In contrast, the second case avoid a detailed estimation of the self-consumption, and it is applied when detailed energy load data are not readily available during the design phase.

The choice between these two balancing types will depend on factors such as the availability of data, the project specific goals, and the level of accuracy required for the assessment of the renewable energy generation and consumption within the building.

2.3. HOT SPOTS IN BUILDINGS LIFE CYCLE

In the context of a streamlined evaluation aiming at reducing the environmental impacts in buildings, one critical question is where it is most effective to make reductions. Generally, LCA applications in the design stage helps the designers in detecting the building aspects or components characterized by a significant high share of the life cycle environmental impact, that are usually addressed as “environmental hot spots”. For instance, a "carbon hot spot" in the context of building LCA refers to a specific area or aspect of a building life cycle where a large amount of carbon emissions is generated.

Identifying and addressing these carbon hot spots is essential for developing more sustainable and environmentally friendly building practices. A reduction of environmental loads in LCA hot spots can lead to significant improvements in the overall life cycle performance of a construction project. Identifying and addressing these hot spots is thus a fundamental principle of sustainable and environmentally responsible building design.

Numerous Life Cycle Assessment (LCA) studies have consistently shown that the use phase of buildings is the primary contributor to total environmental impacts, including energy consumption, CO_2 emissions, and other environmental impacts [35]. Here are some key findings from various studies:

- Asdrubali et al. (Asdrubali et al., 2013) found that the use phase accounts for a significant portion of impacts, with a Contribution to Cumulative Energy Demand (CED) of 77% for detached houses and 85% for office buildings.
- Cuéllar-Franca and Azapagic (Cuéllar-Franca and Azapagic, 2012) calculated that the Global Warming Potential (GWP) contribution of the use phase is as high as 90% for semi-detached or terraced houses in the UK.
- Chau et al. (Chau et al., 2007) estimated that 80-90% of total energy consumption in high-rise office buildings occurs during the use phase.
- Scheuer et al. (Scheuer et al., 2003) determined that the use phase contributes to 93.4% of the global warming potential of residential dwellings.
- Ortiz et al. (Ortiz et al., 2009) further emphasized that the use phase stands out as the most critical stage regarding environmental impacts, constituting approximately 80-90% of the total life cycle impacts for residential dwellings in Catalonia. Their study considered various impact categories, including acidification potential, human toxicity, depletion of abiotic resources, climate change, terrestrial ecotoxicity, and ozone depletion.
- Crawford (Crawford, 2020) tried to pinpoint the areas responsible for the highest environmental carbon emissions throughout the life cycle of a commercial building. The findings highlighted that the most impactful aspect of the building environmental footprint is the use of energy during the operational phase, covering activities such as heating, cooling, lighting, and other services. This operational energy use was found to account for a substantial 76% of global emissions associated with the building life cycle. It is important to note that, with a potential margin of error of ±40%, the contribution of non-operational energy factors may vary between 14% and 34%, highlighting that while still significant, they are less influential than operational energy use.
- Liang et al. (Liang et al., 2023) showed that buildings life cycle carbon emissions are dominated by operational stages, averaging 67%, followed by production and construction phases, averaging 31%, and demolition stages with relatively low emissions, averaging 2%.

These studies underscore the central role of the operational use phase in a building environmental impact and emphasize the importance of focusing sustainability efforts on improving energy efficiency and reducing emissions during this phase. Strategies such as enhancing insulation, optimizing heating, cooling, and lighting systems, and adopting renewable energy sources can have a substantial impact on reducing a building environmental footprint. However, it is essential to consider the entire life cycle of a building, including construction and end-of-life phases, to develop comprehensive sustainability strategies.

2.3.1. ENERGY/CARBON INTENSIVE BUILDING COMPONENTS

In low energy buildings, however, the operational stage results in a lower importance and the embodied impacts acquire a higher share in the life-cycle environmental load of the building. The hot spots of environmental impact can vary depending on the type of building, its location, and the materials and systems used in its construction and operation. Anyway, depending on the typology and function of the building, it is possible to detect some building parts that are characterized by a high environmental impact.

For instance, commonly identified sources of high environmental impacts within buildings include the substructures, structural frames, roofs, external walls, envelope components, in general, and building energy services, including renewable energy generation plants (Victoria and Perera, 2018).
The construction of **foundations and substructures**, particularly in areas with poor soil conditions, can require a substantial amount of concrete and energy. Exploring alternative foundation designs and materials can address this hot spot.

The choice of **structural systems**, such as steel, concrete or timber framing, can significantly influence the embodied impacts. Opting for materials with lower carbon intensity can mitigate this hot spot.
High-rise buildings, for instance, often have more embodied impacts than low-rise ones due to the additional materials required to support lateral loads (e.g., from wind or earthquake stresses). Designing for material efficiency in tall buildings can mitigate this hot spot. However, even if vertical structures should be designed to support horizontal loads, the environmental impact of floors usually represents a very important component in high rise buildings (Foraboschi et al., 2014).
Considering the external envelope, the type and amount of thermos-acoustic **insulation materials** used in a building can significantly affect its embodied environmental burdens. High-performance insulation materials with lower carbon footprints can be selected to reduce emissions (Grazieschi et al., 2021). Incorporating biobased materials, such as wood and bamboo, can help lower the embodied carbon of these materials, as these materials store carbon during their growth.

In the LCA of an office building located in Norway, Rabati et al. (Rabani et al., 2021) considered six main building components: structural foundation, vertical structures and façade (including the lead bearing structure, external walls, insulation layers, water-based interior paint, etc), horizontal structures (such as roof, floors, and floor separators), windows, doors, elevators, staircases, HVAC and heating supply systems (including materials used in the radiators, boilers, ventilation units and ducts and in the hydronic heating distribution system). Looking at the results of this study for the reference office building, its components are listed in **Table 1** in descending order of embodied CO_2 emissions, starting from the highest.

Table 1. *The most impactful building components for Rabani et al., 2021.*

Building component	Embodied carbon	Replacement/renovation
Floors	70.5 kg CO_2/m^2	-
HVAC installations	37.2 kg CO_2/m^2	38.5 kg CO_2/m^2
External roof	31.5 kg CO_2/m^2	-
External walls	29.3 kg CO_2/m^2	8.0 kg CO_2/m^2
Structural foundation	24.5 kg CO_2/m^2	-
Internal vertical partitions	13.2 kg CO_2/m^2	-
Supporting systems	3.2 kg CO_2/m^2	-
Stairs	2.3 kg CO_2/m^2	-

Considering the embodied energy of a prototype NZEB building, Asdrubali et. al (Asdrubali et al., 2020) found the following ranking, displayed in descending order:

- Vertical walls
- Load bearing structures
- PV system (the achievement of the NZEB level required a large PV installation)

- Roof
- Floors
- Energy systems (heat pump and underfloor distribution system)
- Foundation (the building has a superficial foundation that does not require soil excavation)
- Internal vertical partitions
- Stairs

Similar outcomes were found by Asdrubali et al. (Asdrubali et al., 2013) for the embodied environmental impacts of traditional residential and office buildings in Italy (see **Table 2**).

Table 2. *The most impactful building components for Asdrubali et al., 2013 (Ecoindicator 99).*

Detached house	Multi-dwelling buildings	Office building
Vertical envelope (22% of the total)	Vertical envelope (21-22% of the total)	Vertical envelope (30% of the total)
Roof (11% of the total)	Structural elements	Heating system
Sewage system (9% of the total)	Horizontal partitions (floors)	Horizontal partitions (floors)
Structural elements (7.5% of the total)	Internal vertical partitions	Internal vertical partitions
Excavation (6.6% of the total)	Heating system (without cooling)	Roof
Soil retaining structures	Roof	Structural elements
Foundations	Lower horizontal boundary	Excavations
Horizontal partitions (floors)	Sewage system	Foundations
Lower horizontal boundary	Foundations	Lower horizontal boundary
Heating system	Excavations	Soil retaining structures
Internal vertical partitions	Soil retaining structures	Electrical system
External equipment	Plumbing system	Sewage system

Table 3. *Carbon hot spots for Victoria and Perera, 2018 (values for gross internal floor area).*

Carbon hotspot category	Elements (average embodied carbon)
Lead positions	Substructure (161 kg CO_2/m^2), frame (100 kg CO_2/m^2), upper floors (69 kg CO_2/m^2), external walls (60 kg CO_2/m^2) and building services (145 kg CO_2/m^2).
Special positions	Roof (43 kg CO_2/m^2), windows and external doors (16 kg CO_2/m^2), internal walls and partitions (23 kg CO_2/m^2), wall finishes (9 kg CO_2/m^2), floor finishes (26 kg CO_2/m^2) and ceiling finishes (19 kg CO_2/m^2).
Remainder positions	Stairs (8 kg CO_2/m^2), internal doors (1 kg CO_2/m^2), fittings-furnishings and equipment (1 kg CO_2/m^2).

Victoria and Perera (Victoria and Perera, 2018) review the carbon and cost hot spots in buildings, namely the components that are responsible for the 80% of a building embodied carbon. The study is based on a literature review of buildings LCA studies and on the classification of the components in:

- Lead positions elements - that are found to be a carbon hotspot most of the buildings with a probability of occurrence higher than 80%

- Special positions elements - that are found to be a carbon hotspot in most buildings with a 0 < probability of occurrence between 0 and 80%
- Remainder positions elements - that are not found to be a carbon hotspot in any of the buildings considered (probability of occurrence equal to 0)

Table 3 and **Table 4** reports the results of the study.

Table 4. *Cost hot spots for Victoria and Perera, 2018 (values for gross internal floor area).*

Cost hotspot category	Elements
Lead positions	Substructure, frame, roof, external walls, windows and external doors and services.
Special positions	Upper floors, stairs, internal walls and partitions, internal doors, wall finishes, floor finishes, ceiling finishes, fittings, furnishings and equipment.
Remainder positions	None.

2.3.1. ENERGY/CARBON INTENSIVE BUILDING MATERIALS

Energy or carbon-intensive building materials are those materials used in constructions that have a significant environmental impact in terms of energy consumption or carbon emissions throughout their life cycle, from production to disposal. These materials contribute significantly to the carbon footprint of a building. Here are some examples and explanations:

- **Concrete**: concrete production is energy-intensive, particularly due to the energy required for Portland cement production. Cement is a primary component of concrete, and its production process releases a substantial amount of carbon dioxide (CO_2) into the atmosphere. Cement is made by heating limestone, clay, and other materials to extremely high temperatures in a kiln. This process is energy-intensive and releases a significant amount of CO_2, primarily due to the chemical transformation of calcium carbonate (into limestone) to calcium oxide and the release of CO_2 during this process. The most carbon-intensive stage of cement production is the production of clinker. Clinker is the intermediate product in cement manufacturing and is responsible for a large share of the emissions associated with cement production. The high embodied carbon of concrete makes it one of the top contributors to the carbon footprint of buildings. Research is still being done to lessen the carbon footprint of concrete. This includes the use of alternative cements like fly ash, slag, and pozzolans, which can partially replace traditional Portland cement in concrete mixes. These alternatives often have lower embodied carbon. Engineers and architects can also influence the embodied carbon of concrete through mix design. By optimizing concrete mixes to use less cement or incorporating recycled materials, it is possible to reduce the embodied carbon of the concrete. Sustainable construction practices, such as using locally sourced materials and recycled aggregates, can also aid in reducing the overall environmental impact of concrete structures.

- **Steel**: steel production is energy-intensive and has a significant carbon footprint. The production of structural steel involves mining iron ore, refining it into iron, and then converting iron into steel through various processes such as the basic oxygen furnace (BOF) or electric arc furnace (EAF) method. These processes require a significant amount of energy, primarily in the form of electricity. The carbon footprint of structural steel is closely linked to the energy source used in steel production. Steel produced using electricity from fossil fuels typically has a higher carbon footprint compared to steel produced using renewable energy sources or using recycling methods. Structural steel can be made with a significant amount of recycled content. Using scrap steel in the production process reduces the need for virgin iron ore and can lower both embodied energy and embodied carbon. Recycled steel is often used in structural applications, contributing to sustainability efforts. When evaluating the environmental impact of structural steel using LCA, it is important to consider not only its embodied energy and carbon but also its long-term performance and potential for recycling. Steel is highly recyclable, and at the end of its life, it can be reused or recycled into new steel products, reducing the need for virgin steel production.

- **Glass**: the production of glass, especially energy-efficient, high-performance glass used in modern buildings, requires a considerable amount of energy. Energy-intensive glass manufacturing processes, such as float glass production, contribute to its environmental impact.

- **Asphalt**: asphalt used in roofing and pavement requires substantial energy for extraction, refinement, and transportation. The process involves heating and mixing petroleum-based materials, contributing to its carbon intensity.

Table 5. *Embodied energy and carbon of some common building materials.*

Material	**Reference**	**Embodied carbon (A1-A3)**	**Embodied energy (A1-A3)**
Aluminium	(Pomponi et al., 2018)	8230 $kgCO_2/t$	-
Linoleum	(Liang et al., 2023)	7300 $kgCO_2/t$	77.2 GJ/t
Steel	(Cabeza et al., 2021)*	5450-160 $kgCO_2/t$	85-8.9 GJ/t
	(Liang et al., 2023)	2380 $kgCO_2/t$	29 GJ/t
	(Pomponi et al., 2018)	3810 $kgCO_2/t$	-
Glass	(Liang et al., 2023)	1130 $kgCO_2/t$	16 GJ/t
Lime	(Liang et al., 2023)	1190 $kgCO_2/t$	5.3 GJ/t
Cement	(Liang et al., 2023)	735 $kgCO_2/t$	5.5 GJ/t
Concrete (structural)	(Cabeza et al., 2021)*	240-76 $kgCO_2/t$	3.1-0.57 GJ/t
	(Pomponi et al., 2018)	170 $kgCO_2/t$	-
Bricks	(Liang et al., 2023)	292 $kgCO_2/t$	2.0 GJ/t
	(Pomponi et al., 2018)	520 $kgCO_2/t$	-
Wood	(Liang et al., 2023)	200 $kgCO_2/t$	1.8 GJ/t
Engineered timber	(Pomponi et al., 2018)	680 $kgCO_2/t$	-
Asphalt	(Liang et al., 2023)	162 $kgCO_2/t$	3.0 GJ/t
EPS	(Grazieschi et al., 2021)	1.9–3.5 kg CO_2eq/m^2 (R=1 m^2k/W)	44–78 MJ/m^2 (R=1 m^2k/W)
Glass wool	(Grazieschi et al., 2021)	0.6–1.2 kg CO_2eq/m^2 (R=1 m^2k/W)	16–31 MJ/m^2 (R=1 m^2k/W)
Rock wool	(Grazieschi et al., 2021)	1.4–4.2 kg CO_2eq/m^2 (R=1 m^2k/W)	21–66 MJ/m^2 (R=1 m^2k/W)
PUR	(Pomponi et al., 2018)	3000 $kgCO_2/t$	-
HDPE	(Pomponi et al., 2018)	1610 $kgCO_2/t$	-
PV panel	(Finnegan et al., 2018)	219-610 $kgCO_2/m_2$	-

* max-min values; minimum values for steel are referred to 100% recycled materials.

- **Insulation materials**: some insulation materials, such as foam boards or spray foam insulation, are made from petrochemicals and can have a high carbon footprint due to the energy-intensive manufacturing process. However, their use in improving energy efficiency in buildings can offset this impact over time.

Grazieschi et al. (Grazieschi et al., 2021) showed that traditional inorganic insulation materials, such as glass wool and stone wool, have competitive embodied impacts in comparison with fossil fuel derived one (EPS, XPS, polyurethane, PIR, etc.). The application of natural/organic insulation panels should, instead, been adequately evaluated since, sometimes, they exhibit higher impacts for the same insulation capacity.

- **Aluminium**: aluminium production is energy-intensive, and its use in building components, like window frames, can contribute to the embodied carbon of a structure. Although aluminium is not as commonly used in building structures as concrete and steel, its use, even if in small architectural applications, can generate significant environmental impacts.

- **Bricks and masonry blocks:** the manufacturing of clay bricks and concrete blocks involves high-temperature kiln firing, which consumes energy and releases CO_2 (Asdrubali et al., 2023). As a consequence, traditional clay bricks are relatively energy-intensive compared to other wall materials. The use of these materials in large quantities can significantly contribute to the embodied energy/carbon of buildings.

Table 5 reports literature values of embodied energy and carbon of some common construction materials.

2.4. ECONOMIC AND ENVIRONMENTAL OPTIMIZATION

An important aspect raised by the EPBD recast is the provision of cost-optimality methodology framework.

The scientific literature on the **cost optimization** of buildings or of energy retrofits is quite vast. The methodologies implemented usually make use of genetic algorithms (e.g., the Nondominated-and-crowding Sorting Genetic Algorithm II, namely NSGA-II, particle swarm optimization algorithms, the simulated annealing, …), derivative-free optimization algorithms, performance of the optimization methods, hybrid algorithms (Machairas et al., 2014).

The effectiveness of a specific combination of retrofit interventions depends on different aspects ranging from the climatic conditions of the area, the characteristics of the building to be refurbished, the renewable energy availability in the area, etc. The scope of the optimization is to find a cost-optimal mix of interventions that is able to minimize the Life Cycle Cost (LCC) of the construction or of the retrofit intervention.

Sometimes a **multi objective optimization** is performed and the economic analysis is integrated with other evaluations, such as the environmental impact assessment or the comfort zone.

In recent years, the energy and **environmental optimization** are gaining an increasing attention due to the ever-growing sensitivity to climate change and energy conservation issues. In this field of research, the application of LCA is gaining a growing attention due to the fact that it represents a methodology that is able to quantify the environmental impacts of a product or of a service in a quantitative way. The scopes of the LCA optimization methodologies are generally to minimize a specific environmental impact category, (e.g., the Global Warming Potential (GWP)), some indicators of resource use (e.g., the Cumulative Energy Demand (CED)) or some aggregated impact indicators (e.g., Ecoindicator 99, Recipe, etc.).

When considering a life cycle optimization, it is important to investigate the relation between the **operational impacts and total environmental burdens** in a new building or retrofit interventions. The implementation of energy efficiency measures and the integration of renewable systems, in fact, generally reduces the operational impacts while increasing the embodied ones. The optimization should demonstrate if, through the implementation of different energy saving strategies or renewable installations, it is possible to reduce the overall environmental impact of the interventions or if the burden shifting experienced turns out to be detrimental in the life cycle.

The following **Figure 1** reports the relationship between the operational primary energy and life cycle energy of a bunch of buildings: the data are gathered from three literature sources. A linear regression approximates the dataset with a R^2 equal to 0.95, confirming that a reduction of the operational energy is followed by a comprehensive reduction of the life cycle energy as well. However, this result is strongly linked to the negligible contribution of the embodied components, particularly for traditional buildings, and to the methodological guidelines followed for the implementation of the LCA.

More detailed analyses should be performed to investigate what happens in the case of low-energy buildings: in these cases, it is essential to verify the entity of the **life cycle performance improvements** that are achievable in comparison with traditional constructions and to show how far it is possible to arrive in the **containment of the trade-off on embodied components** when the reference is the local practice for NZEBs. The Norwegian ZEB/ZEN centre has already shown that, considering five Norwegian NZEBs, their embodied GHG emissions can arrive to account for more than the half of the total life cycle ones: in particular, the emissions attributable to the envelope or the production and replacement of building materials represented the 65% and the 55–87% of the total (Wiik et al., 2018).

It is thus fundamental to perform these types of evaluations and optimizations during the preliminary design phase as this methodological approach guides the overall process into the right track towards sustainability. This report demonstrates how early design phase calculation can be performed using ARV's demo projects as cases.

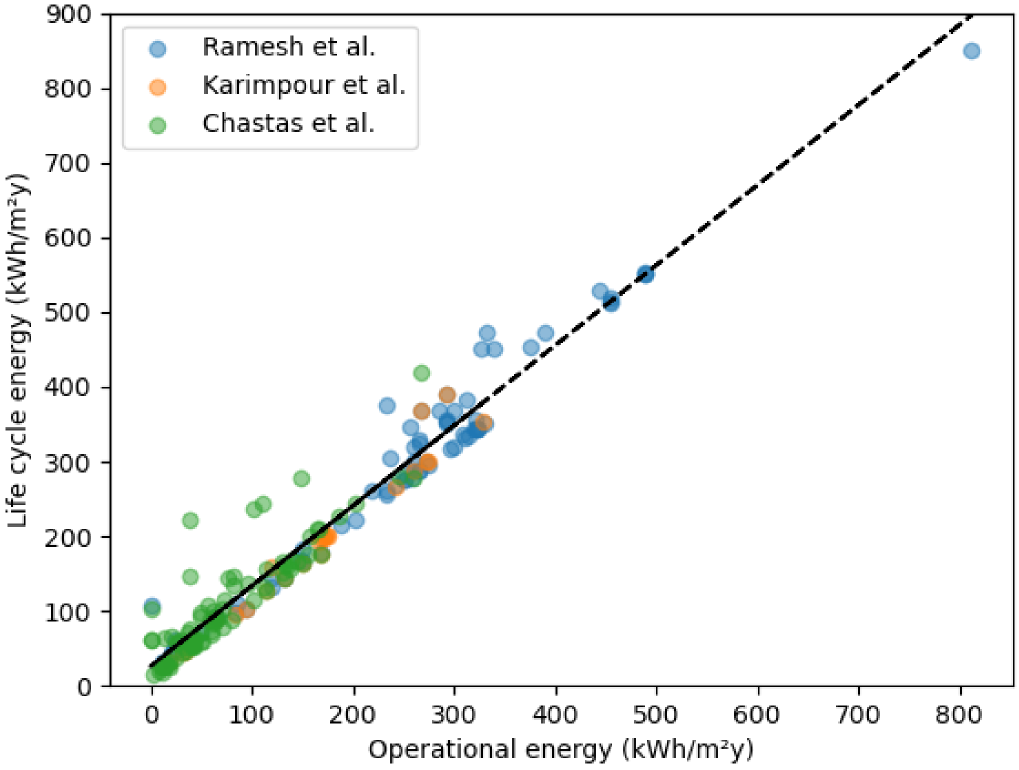


***Figure 1**. Life cycle energy versus operational energy in buildings (data sources: Ramesh et al., Karimpour et al., Chastas et al.).*

3. METHODOLOGICAL APPROACHES

The application of the methodology targets the achievement of the following EIC that were declared in the ARV project proposal:

- **EIC5** - Reduction of greenhouse gas emissions towards zero (in tCO_2-eq/year) for the total life cycle compared to the current situation shown through cradle-to-cradle LCA**.**
- **EIC6 -** Reduction of the embodied energy in buildings by 50 % without concessions with respect to energy consumption and comfort.
- **At least 20% reduction** in life cycle costs compared to local current practice.

3.1. GOAL & SCOPE DEFINITION

3.1.1. SCENARIOS DEFINITION

The goal or scope of the analysis is linked to the **quick selection of design alternatives and the verification of the effectiveness of the environmental and economic strategies implemented by the demonstration projects to achieve sustainability**.

The streamlined methodology is, in fact, developed to specifically support the design stage. In particular, the following scenarios are considered:

New constructions

- Nearly Zero Energy Building (NZEB), which is the legal minimum standard for new buildings in Europe.
- Low energy, which represents a design scenario with an ambition that is below the legal minimum.
- Plus-energy building (PEB), which exceeds the legal minimum standard but is a requirement for the ARV project.

Renovations of existing buildings

- Status Quo, which represents the situation before the renovation.
- Nearly Zero Energy Building (NZEB), which is the minimum requirement for the ARV project.
- Low-energy renovation, which represents a renovation with an ambition that is below the NZEB but within the national energy efficiency laws and regulations.
- Plus-energy renovation, which considers an optional scenario with an ambition level that exceeds the NZEB standard. This scenario could be even only theoretical with the scope of verifying its technical, normative, economic, and environmental feasibility.

3.1.2. FUNCTIONAL UNIT

The accomplishment of the scope of the analysis is strongly linked to the selection of a coherent functional unit (FU). For uniformity purposes and to normalize the results for the size of the building, the FU that will be considered by all case studies is equal to:

- the square meter of gross internal area

Moreover, the cumulative life cycle impacts will also be normalized for the service life of the building (50 years, as suggested by the PCR; 60 years for the Norwegian demo, as stipulated in NS 3720:2018, Method for greenhouse gas emissions of buildings). In this way the results should be reported in terms of kWh/m^{2}y, kg CO$_2$/m^{2}y or €/m^{2}y. If a building component has a useful life that is lower than 50 years, its substitution should be taken into account using the following equation:

$$NR_i = ceiling\left[\frac{L}{L_{m,i}} - 1\right]$$

where

$L_{m,i}$ is the life span of material/product/component i;
NR_i is the number of replacements for material/product/component i;
L is the reference study life period for the building (50 years).

Some possible reference values, derived from experience, that could be adopted for the service life of building components are reported in **Table 6**.

Table 6. *Reference service life for some building components.*

Material	Description	Service life (years)
Concrete	Load bearing structures	100
Steel	Load bearing structures	100
Timber	Load bearing structures	80
Roof covering	External layer of the roof	50
Wood	Wooden elements exposed to weather	20
Windows	All typologies	35
Internal partitions	Hollow brick blocks	50
EPS	External insulation coating	50
PV panel	Building services (BIPV, BAPV)	25
Heat pumps	Building services	25
Boilers	Building services	25

3.1.3. BOUNDARIES OF THE ANALYSIS

Figure 2 reports the life cycle modules considered by the EN 15804/EN 15978 standards.

The following aggregation was proposed for the present evaluations:

- Embodied impacts /investment costs (A1-A5 + B4)
- Operational including the energy demand/costs for heating, cooling and domestic hot water (B6)
- End-of-life (C1-C4)
- Benefits achievable from energy exportation, reuse, recycling and energy recovery of building materials, carbon sequestration (D)

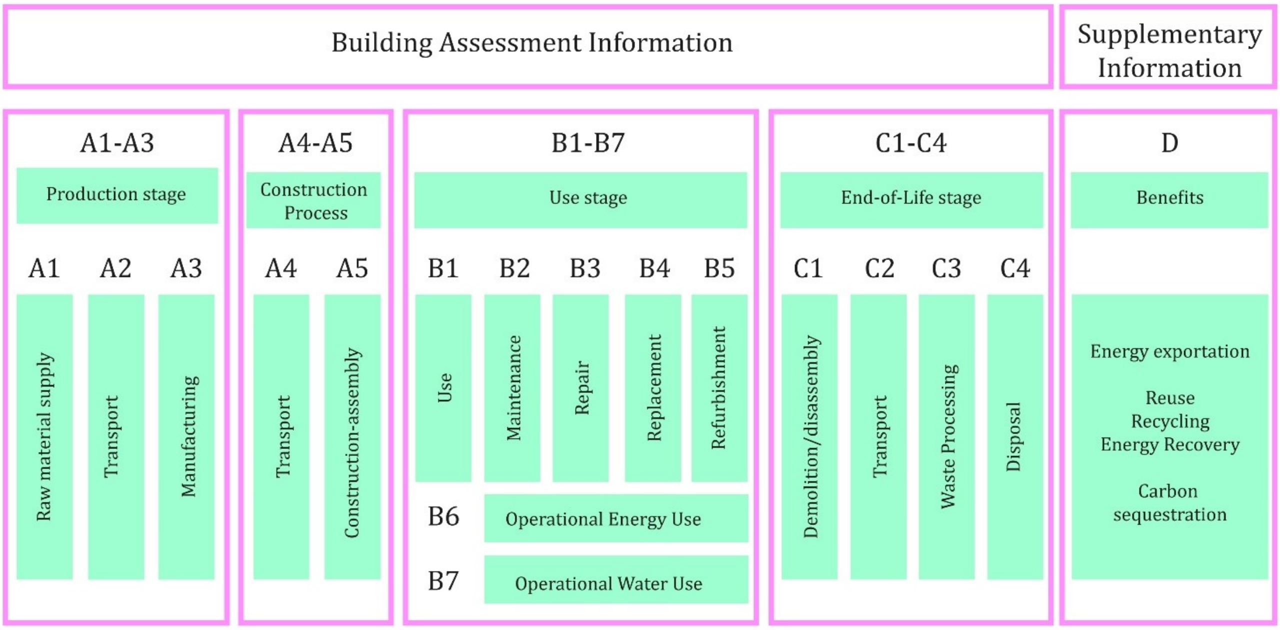


***Figure 2**. Life cycle stages for buildings LCA (EN 15804/EN 15978).*

3.1.4. ALLOCATION APPROACHES IN BUILDING RENOVATIONS

When analysing building renovations, it is possible to adopt different methodological approaches to consider the impacts or cost related to the materials that are part of the existing building and maintained after the renovation. In assessing the renovation, the main methodological challenge is whether and how to include and account for the existing materials.

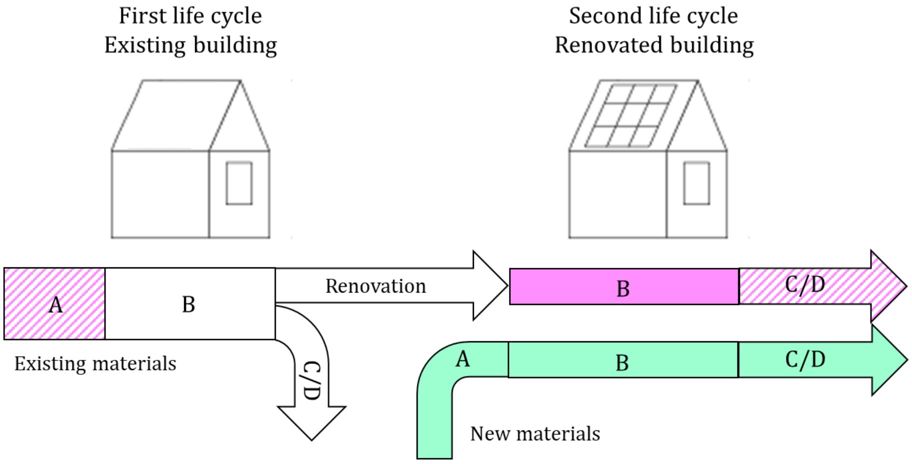


***Figure 3**. 50:50 approach (A: production; B: use, maintenance, repair and replacement; C/D: end-of-life). Modules that are considered for the 50% are hatched.*

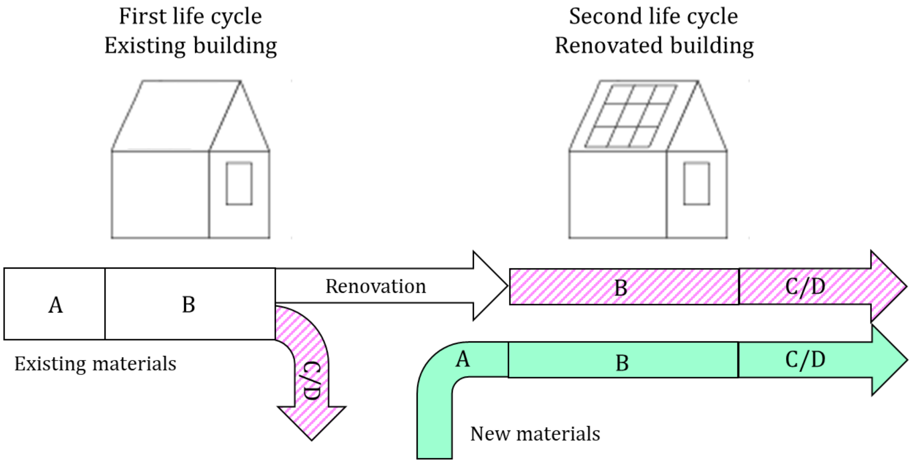


***Figure 4**. Burden free approach (A: production; B: use, maintenance, repair and replacement; C/D: end-of-life). Hatched modules are occasionally considered.*

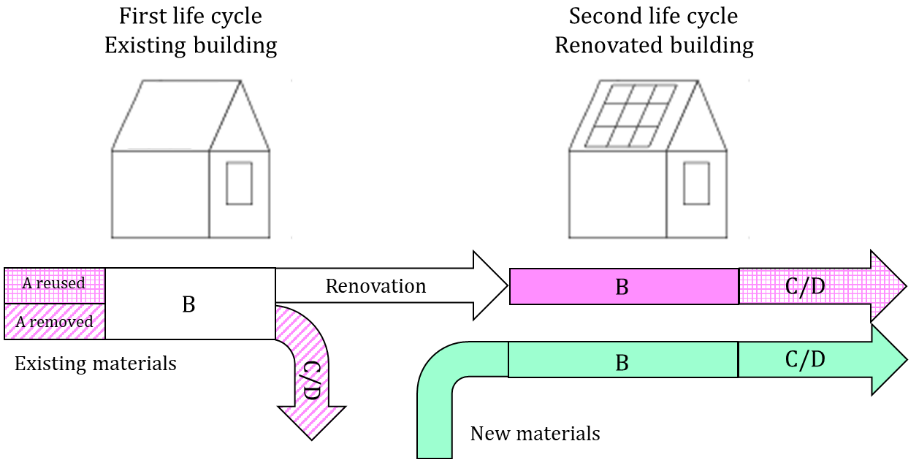


***Figure 5**. Residual value approach (A: production; B: use, maintenance, repair and replacement; C/D: end-of-life). The unamortized impacts of hatched modules are accounted through a flat periodization within the RSL. Materials that are removed during the renovation are occasionally considered.*

Three main approaches were detected after reviewing the literature on this topic (Kjær Zimmermann et al., 2022; Obrecht et al., 2021):

- Allocation using 50:50, avoided burden approach.
- Allocation using the burden free approach.
- Allocation using the residual value or depreciation approach.

In the **50:50 approach**, the burdens of the reuse of existing materials are equally distributed between the first and second cycles. Specifically, 50% of the environmental impacts of production occur in the first life cycle, namely the one before the renovation, while the remaining 50% and reprocessing impacts occur in the second life cycle, namely the one following the renovation (see **Figure 3**). The PEF approach adopts a 50:50 methodology to distribute benefits and burdens across multiple life cycles, but it adds quality factors to consider down-cycling and market demand for recycled products: in this case, half of the environmental impacts of production are assigned to the first life cycle, while the remaining half is allocated to the second life cycle together with the refurbishment impacts weighted by quality factors.

The main challenge in using the PEF method is that the quality factors are sometimes difficult to determine.

The **burden free approach** (or cut-off approach) considers that the environmental impacts of the production phase of a product/building are attributed to its first user and follow the "polluter pays" principle. In the case of building renovation, the impacts and costs of the existing materials are allocated to the life first life cycle, namely to the one preceding the renovation. The second life cycle, which follows the renovation, bears only the impacts or costs linked to the installation and production of the new materials, their maintenance, replacement, and end-of-life (see **Figure 4**). Occasionally also impacts and costs related to the end-of life of existing materials, to their maintenance and replacement during the life cycle that follows the renovation are accounted.

The **residual value or deprecation approach** (**Figure 5**) is basically based on the amortization of costs and impacts in the reference service life of building products and materials. The unamortized impacts and costs are allocated to the second life cycle of the building, thus to the renovation. A linear distribution is commonly used for determining residual values by depreciating impacts over time.
In particular, at the time of refurbishment, remaining unamortized impacts (or residual values) of existing materials should be allocated to the second life cycle with the impact/cost allocation being equally distributed across the RSL of the products.

When modelling the environmental impacts of building renovations using allocation, a valuable way for improving LCA results is to adapt current production processes with those employed in the past. In fact, impacts of material production were different in the past due to differences in manufacturing processes, transportation, and energy mixes. Tajda Potrč Obrecht et al. (Potrč Obrecht et al., 2021), for instance, showed higher impacts attributable to the building materials produced in the 1970 (+8 to14% in comparison with the current production chains). The application of dynamic life cycle methods is very useful both for modelling future scenarios but also for considering past impacts in the LCA of building refurbishments. The adoption of this approach, however, will result in a higher workload for LCA practitioners and in a consequent extension of the modelling time which does not fit into the scopes of the streamlined approach promoted at this stage of the ARV project.

3.1.5. LIFE CYCLE INVENTORY

The life cycle inventory (LCI) will be compiled considering the results of the simulations regarding the energy performance of buildings and the preliminary cost/bill of quantities evaluations performed during the design stage. This information could be gathered from:

- BIM models (IFC files)
- Static or dynamic energy calculation models (EnergyPlus, TRNSYS, etc.)
- Computations performed by structural engineers
- Construction and demolition waste computation

The information used can be subjected to a high uncertainty since we are speaking about preliminary calculations aiming at selecting design alternatives.

3.2. STREAMLINED LIFE CYCLE ASSESSMENT

The objectives of the application of streamlined life cycle assessments are to quantify the environmental impacts linked to the different design solutions considered by each demo group for the ARV interventions.
Following the EN 15978, the life cycle phases that are considered are: production phase (stages A1-A3), construction phase (A4-A5), operational energy use (stage B6), replacement (stage B4) and disposal

(stages C3-C4). Phase D, that includes the benefits and loads outside the system boundary (e.g., in relation to the renewable energy produced and exported into electricity grids) is considered separately. Concerning stage A5, it is usually very difficult to find reliable values for the energy requirement of construction activities. This is why the incorporation of this stage into the analysis relies on the data availability from the demonstration groups.

3.2.1. LIFE CYCLE IMPACT ASSESSMENT AND INDICATORS

The analysis considers only two main indicators:

- the Cumulative energy demand (CED), that quantifies the overall primary energy demand and allows to split the renewable part from the non-renewable one.
- the Global Warming Potential (GWP) that quantifies the greenhouse gas emissions in terms of CO_2 equivalents.

The **embodied energy ($E_{p,P}$)** is the primary energy utilized during the manufacturing of the building materials. It is basically calculated as the sum of the initial embodied energy (i.e., the energy requirement for the construction of the building) and the recurring embodied energy (that is linked to building components substitution).

$$E_{p,P} = E_{p,Pi} + E_{p,Pr} = \frac{\sum_j m_j \cdot M_j}{S \cdot L} + \frac{E_{p,C}}{L} + \frac{\sum_j m_j \cdot M_j \cdot ceiling\left[\left(\frac{L}{L_{mi}}\right) - 1\right]}{S \cdot L}$$

Where:

$E_{p,Pi}$ – initial embodied primary energy in a product stage [kWh/m²y];
$E_{p,Pr}$ – recurring primary energy in a product stage [kWh/m²y];
m_i – quantity of building material (j) in kg or tons;
M_i – energy content of material (j) per unit quantity (e.g., in kWh of primary energy per kg/ton of material);
$L_{m,j}$ – the estimated service life for product/component j in years;
L – reference study period [50 years];
S – gross floor area of the building [m²];
$E_{p,C}$ – non-renewable primary energy for a construction stage A5 [kWh/m²].

The **operational energy or primary energy in the use stage ($E_{p,U}$)** is the primary energy required to maintain adequate comfort conditions in the building. It includes the energy for HVAC (heating, ventilation, and air conditioning), domestic hot water, and lighting. In Deliverable 2.1 the following definition was given:

$$E_{p,U} = \sum_i E_{p,del,i} - \sum_i E_{p,exp,i} = \sum_i \int P_{del,i}(t) \cdot w_{del,i}(t) \cdot dt - \sum_i \int P_{exp,i}(t) \cdot w_{exp,,i}(t) \cdot dt$$

Where

$E_{p,U}$ - the primary energy in the use stage [kWh/m²y];

$E_{p,del,i}$ - delivered primary energy per energy carrier i [kWh/m²y];

$E_{p,exp,i}$ - exported primary energy per energy carrier i [kWh/m²y];

$P_{del,i}$ - the delivered power on site or nearby for energy carrier i [kW/m²];

$w_{del,i}$ - the primary energy factor for the delivered energy for energy carrier i [-];

$P_{exp,i}$ - the exported power on site or nearby for energy carrier i [kW/m²];

$w_{exp,i}$ - the primary energy factor of the exported energy for energy carrier i [-].

Since in this assessment the exported energy is displayed separately in module D and the primary energy factor is considered constant in time, the primary energy in the use phase is basically determined multiplying each yearly delivered final energy consumption of the building $FE_{del,i}$, split for each energy vector i, for its respective annual primary energy conversion factor $(w_{del,i})$.

$$E_{P,U} = \sum_i E_{p,del,i} = \sum_i \int P_{del,i}(t) \cdot w_{del,i}(t) \cdot dt \ = \sum_i FE_{del,i} * w_{del,i}$$

The **primary energy in the end-of-life stage ($E_{p,EoL}$)** represents the primary energy expenditure for the demolition/disassembling of the building ($E_{p,D}$), for the transportation of the waste materials to the treatment facilities ($E_{p,T}$), for the waste treatment ($E_{p,C3}$) and eventual landfilling ($E_{p,C4}$).

$$E_{p,EoL} = E_{p,D} + E_{p,T} + E_{p,C3} + E_{p,C4}$$

The overall **life cycle CED** (or $E_{p,LC}$ to comply with D2.1) is equal to the sum of embodied, operational and end-of-life components. All the components should be decomposed into the renewable and non-renewable parts.

$$CED = E_{p,LC} = E_{p,P} + E_{p,U} + E_{p,EoL}$$

The **embodied GWP (B_P)** is defined in a similar way.

$$B_P = B_{Pi} + B_{Pr} = \frac{\sum_i m_i \cdot w_{mat_i} + B_C}{L} + \frac{\sum_i m_i \cdot w_{mat_i} \cdot ceiling\left[\left(\frac{L}{L_{mi}}\right) - 1\right]}{L}$$

Where:

B_{Pi} – initial emissions in the production stage [kg CO_2eq/y];
B_{Pr} – recurring GHG emissions in the production stage [kg CO_2eq/y];
B_C – emissions in a construction stage (negligible for construction works based on prefabrication) [kg CO_2eq].
m_i – quantity of building material i [kg];
w_{mat_i} – emission content of material i per unit quantity [kg CO_2eq/kg or ton];
L – reference study period [50 years];
L_{mi} – life span of the material i [y].

The biogenic carbon can be considered in the calculations, but it should be reported in a separated sub-module D.

The **operational GWP (B_U)** represents the sum of the greenhouse gas emissions generated by the energy absorptions for heating, ventilation, air conditioning, domestic hot water, and lighting.

$$B_U = \sum_i B_{E_{p,del,i}} = \sum_i \int P_{del,i}(t) \cdot w_{CO_2,del,i}(t) \cdot dt$$

Where:

B_U – emissions in the use stage [kg CO_2eq/y];
$B_{E_{p,del,i}}$ – emissions from delivered primary energy per energy carrier i [kg CO_2eq/y];
$P_{del,i}$ – delivered power for energy carrier i into object of assessment [kW];
$w_{CO_2,del,i}$ – emission coefficient for delivered energy carrier i [kg CO_2eq/kWh];

Considering the emission factor constant in time, the operational GWP in the use phase can be basically determined as follows:

$$\boldsymbol{B_U = \sum_i B_{E_{p,del,i}} = \sum_i FE_{del,i} \cdot w_{CO_2,del,i}}$$

The emissions savings due to renewable energy exportation should be reported in module D and can be determined as follows:

$$\boldsymbol{B_{U,module\ D} = -\sum_i B_{E_{p,exp,i}} = -\sum_i \int P_{exp,i}(t) \cdot w_{CO_2,exp,i}(t) \cdot dt}$$

$\boldsymbol{B_{E_{p,exp,i}}}$ – emissions from exported primary energy per energy carrier $\boldsymbol{i}$ [kg CO$_2$eq/y];
$\boldsymbol{P_{exp,i}}$ – exported power for energy carrier $\boldsymbol{i}$ out of object of assessment [kW];
$\boldsymbol{w_{CO_2,exp,i}}$ – emission coefficient for exported energy carrier $\boldsymbol{i}$ [kg CO$_2$eq/kWh].

In the streamlined assessment proposed $\boldsymbol{w_{CO_2,exp,i}}$ is equal to $\boldsymbol{w_{CO_2,del,i}}$.

The **end-of-life GWP ($\boldsymbol{B_{EoL}}$)** groups the emissions linked to the deconstruction of the building and to the transportation of the waste materials to the treatment facilities.

$$\boldsymbol{B_{EoL} = \frac{B_D + B_T + B_{C3} + B_{C4}}{L}}$$

Where:

$\boldsymbol{B_{EoL}}$ - emissions in the end-of-life stage [kg CO$_2$eq/y];
$\boldsymbol{B_D}$ - emissions from de-construction demolition of the building [kg CO$_2$eq];
$\boldsymbol{B_T}$ - emissions from transporting waste materials [kg CO$_2$eq];
$\boldsymbol{B_{C3}}$ - emissions from treatment of waste materials [kg CO$_2$eq];
$\boldsymbol{B_{C4}}$ - emissions from landfilling of waste materials [kg CO$_2$eq];
$\boldsymbol{L}$ - reference study period [50 years].

The **life cycle carbon** sums the three components: embodied, operational, and end-of-life carbon.

$$\boldsymbol{B_{LC} = GWP_{LC} = B_P + B_U + B_{EoL}}$$

3.3. STREAMLINED LIFE CYCLE COST ASSESSMENT

The Life Cycle Costs (LCC) is a methodology that allows the evaluation of the global cost of a building considering its entire life cycle.

The global cost is represented by the sum of purchasing costs, of the expenses sustained during its use and maintenance, and of the eventual residual value of an object at the end of its useful life.
Following a structure that traces the one adopted for the LCA, the streamlined LCC assessment includes:

- Production phase (stages A1-A5),
- Use phase (related to the energy use stage B6),
- Replacement phase (stage B4)
- End-of life phase (stages C1-C4).
- Benefits beyond system boundaries (stage D), that sum up the economic benefits related to the exportation of renewable energy or the residual values of materials after the demolition of the building.

It should be noted that modules B2 (cleaning) and B3 (maintenance) can be quite relevant in the LCC of a building. However, in the proposed streamlined assessment, these two modules were left as optional. **Table 7** shows the LCC structure agreed.

Table 7. *LCC structure*

Phase	**Cost description**	**LCA stage**	**Time**	**Terms**		
Production	Raw materials Transport Manufacturing	A1 A2 A3	t_0	A1-A3 is contained in investment cost		Total cost C_g
Construction	Transport Construction	A4 A5/B5	t_0	Investment/refurbishment cost C_i		
Use	Use of components Operational costs *insurances, taxes, …*	B1 B1	t_1, …, 50	Operational cost C_{op}	Annual cost C_a	
	Maintenance Replacements	B2-B3 B4		Maintenance cost C_m		
	Energy use *heating* *cooling* *ventilation* *DHW* *lighting* *appliances etc.*	B6		Energy cost C_e		
	Water use	B7		Optional		
End-of-life	Residual value	D	50	Final/residual value Val_F		
	Demolition Transport Recycling Disposal	C1 C2 C3 C4		Demolition or disassembly cost + cost of recycling + cost upgrading + disposal cost + C_{disp}		
Benefits	Benefits	D	t_1, …, 50	Energy gain G_{en}		

When it comes to life cycle cost assessment for buildings, it is essential to refer to the specific standards for detailed guidance and requirements applicable to your context. The following standards represent a methodological reference for the implementation of life cycle cost in the building sector and offer a framework for evaluating life cycle costs, considering various factors such as design, construction, operation, maintenance, and end-of-life phases:

- **EN 15459:2008 — Sustainability of construction works - Assessment of buildings' environmental performance —** outlines principles and provides guidelines for assessing the life cycle costs (LCC) of buildings and civil engineering works. It covers various cost aspects throughout the life cycle, including design, construction, operation, maintenance, and end-of-life phases. EN 15459 aims to facilitate consistent and comprehensive LCC assessments in the construction industry. It also provides guidelines for assessing the service life of construction works, contributing to a comprehensive understanding of longevity considerations.

- **ISO 15686-5:2008 — Buildings and constructed assets - Service life planning - Part 5: Life cycle costing —** specifically focuses on service life planning for building components and systems. It provides a framework for assessing the expected service life of these elements, aiding in the determination of their durability, and helping stakeholders make informed decisions regarding maintenance, repair, and replacement strategies. This standard contributes to a systematic approach to life cycle planning in construction projects.

- **EN 16627:2015 — Sustainability of construction works - Assessment of social performance of buildings - Calculation methodology —** addresses the determination of the service life of buildings. It complements other standards by providing guidance on evaluating the expected duration of a building's life cycle, considering various factors such as materials, construction methods, and environmental conditions.

The previous standards offer a structured approach to evaluating the duration and life expectancy of various components within the life cycle of a system or building. The determination of the service life of building components is particularly relevant to the Level(s) indicator 6.1 within the LCC framework, emphasizing the importance of standardized methodologies for estimating and evaluating the life spans of various elements in construction projects.

3.3.1 SYSTEM BOUNDARIES AND INDICATORS

The aggregation of the data and of the results of the LCC should be in agreement and equivalent to the one proposed in the streamlined LCA, so that the coherence in the outcomes of the two analyses can be verified.
The following system boundaries are thus adopted:

- Initial/recurring investment (C_i+C_{m-B4}, which are parallel to LC phases A1-A3 and B4)
- Operational costs (C_{e-B6}) n.b. only the ones related to energy use, in agreement with the streamlined LCA (LC phase B6)
- Disposal costs (C_{disp}, which corresponds to LC phases C3, C4)
- Expected benefits (e.g., from renewable energy production valorisation: G_{en}; this LCC module relates to LC phase D)

LCC provides a range of possible result indicators which can be used for an assessment. Amongst these are the net present cost (NPC), net present value (NPV), annual cost (AC) or annual equivalent value (AEV) (s. EN 16627:2015 Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods). Additional indicators include payback period, net savings or net benefit, savings to investment ratio or adjusted internal rate of return ISO 15686-5). In this analysis, various indicators were employed, some of which incorporate future cost discount values, while others do not.

To assess life cycle costs and life cycle emissions simultaneously when comparing scenarios, we used cost effectiveness of greenhouse gas emissions savings.

3.4. OVERVIEW

The previous sections describe the streamlined methodology for the application of LCA/LCC that was discussed and agreed between the partner of the ARV project.
The most important necessity expressed by all the participants when applying LCA during the design process is to speed up calculations even through a simplified modelling. In fact, even though there may be approximations, providing rough or partial estimates of the environmental impacts throughout the life cycle, it is still preferable to completely disregard these impacts.

To achieve this goal, the following simplifications were made:

- Use of general datasets even if rough results could be obtained. In fact, a common challenge when applying LCA/LCC during the design process is that, during the initial design phases, there is a multitude of design options while the necessary data for LCA calculations pertaining to specific products are often limited or scarce.
- Limit the spatial boundary of the analysis to the building level, thus excluding the neighbourhood scale which adds much more complexity to the calculations.
- Simplify the inventory analysis by concentrating on the key building components that significantly contribute to the overall building mass or to a specific impact category.
- Simplify calculations by focusing on the only impacts linked to climate change (e.g., GWP) or considering indicators of resource use (e.g., CED).
- Simplify the inventory analysis and calculations by only considering the elements that would change from one scenario to another and the differences compared to a baseline scenario.
- Make use of BIM or CAD models, already developed during the design phase, to extract data useful for the analysis.
- Add an LCA plug-in within BIM software to streamline the integration of data and processes essential for both methodologies, thereby reducing the time required for data management across separate programs.

To conduct a simplified LCA analysis meeting the requirements already described, the most simplified way is to perform basic calculations in Excel sheets. All the participants had the experience needed. However, various types of tools are now accessible for quick LCA applications related to buildings: Ecosoft, EcoEffect, Equer, Legep, Envest, Beat, etc. More advanced and comprehensive LCA software could be considered such as SimaPro or Gabi. Considerably more expertise is required to effectively navigate and utilize this software. Moreover, the presence of a licence does not facilitate their large-scale usage.

The following tools were considered more in detail for the assessment (see **Table 8**).

Table 8. *LCA tools that were considered suitable for the assessment.*

Name	Country	Database	Rights of use	Website
CAALA	Germany	Ökobau.dat	Licensed	caala.de
GPR Building	Netherlands	Dutch Environmental Database (NMD)	Free	milieudatabase.nl
One Click LCA	UK	Various, Spanish EPDs	Licensed	oneclicklca.com
Open LCA	Germany	Various	Free	openlca.org
Reduzer	Norway	Generic databases, Norwegian EPDs	Free	reduzer.com
SimaPro	Netherlands	Ecoinvent	Licenced	simapro.com

Table 9 and **Table 10** recap:

- Temporal system boundaries (life cycle phases included and study period)
- Indicators considered (GWP, CED, NPV, total cost)
- Tools used for the modelling of the energy demand of the building (module B6)
- The tool finally selected for the LCA and the related background database
- The source of cost data

Table 9. *LCA tools and system boundaries in the demo projects.*

Demo project	LCA tools used / developed	Indicators considered	Study period	Life Cycle phases included	Tools used for life cycle phase B6
Oslo	OneClick LCA, Reduzer	GWP – kg CO_2e/m^2	60 years	A1-A4, B4, B5; B6 considered separately	Simien
Utrecht	GPR	CED - kWh/m^2 GWP - kg CO_2e/m^2	50 years	All	Uniec3
Palma	One Click LCA	GWP – kg CO_2e/m^2	50 years	A1-A5, B4, B5, B6, C1 (new construction only), C2-C4, D considered separately	TRNSYS
Karvina	One Click LCA	GWP - kg CO_2e/m^2	50 years	A1-A4, B4, B5; B6; C2, C3; D	Energie 2023
Trento	SimaPro (Ecoinvent v3.9)	CED - kWh/m^2y GWP - kg CO_2e/m^2y	50 years	A1-A4, B4, B6, C1-C4, D	TerMus version 50.00d BIM

Table 10. *LCC tools and system boundaries in the demo projects.*

Demo project	LCC tools used / developed	Indicators considered	Study period	Life Cycle phases included	Source for cost data
Oslo	Excel spreadsheet	NPV (net present value) in Euros	60 years	A1-A3, B4, B5; B6	Norsk prisbok
Utrecht	Excel spreadsheet was developed	NPV in Euros	50 years	All	Company information
Palma	Global cost module programmed in Python, used in the prototype of the urban tool for the Palma demo	Global cost (incl. energy, investment, maintenance and replacement costs) in Euros per dwelling (only for the renovation case)	50 years	A1-A5, B2-B3. B4, B5, B6, D (note: benefits from the export of solar energy are considered directly in the energy costs (B6))	CYPE, energy systems datasheets, manufacturers data
Trento	Excel spreadsheet	Total cost in Euros	50 years	A1-A4, B4, B6, D	Company cost computation

4. APPLICATIONS

This chapter includes the preliminary results for each demo project obtained using the LCA/LCC methodologies described in the previous sections. Each demo's chapter specifies the methods in more detail for calculating the energy use, life cycle emissions and life cycle costs for the respective demo. All demos define several energy target scenarios and evaluate the corresponding emissions. Some of them yielded supplementary results pertaining to primary energy usage (renewable and non-renewable) and life-cycle costs.

4.1. KARVINA DEMO

4.1.1. NZEB, PEB, LOW-E BUILDINGS: DEFINITIONS

Nearly zero energy building

The obligation to build new nearly zero-energy buildings is gradual, with the obligation for public authority buildings introduced first in 2016. For all other owners, the obligation was phased from 2018 to 2020 depending on their size. As a result of the gradual ramp-up, since 1 January 2020, all buildings for which an application for a building permit is submitted must meet the Nearly Zero Energy Building Standard. However, for the set of requirements before 2022 (NZEB I), the term "near-zero energy building" was still rather exaggerated. The term does not imply that such a building will consume almost no energy or that it will have an almost zero balance of energy consumed and produced. The set-up allowed for a near-zero energy building (single-family house, apartment building) to be a well-insulated building without the use of any renewable energy source, heated by a gas condensing boiler, or even in the case of an office building, a building heated by electricity, highly demanding the depletion of non-renewable resources.

In June 2020, a new decree 264/2020 Coll. on the energy performance of buildings was issued, which brings a number of changes in both the assessment method and the requirements for construction, especially from 2022. For the reference building, its parameters have been modified. While there are no significant changes on the required envelope construction quality side, there is some tightening for the technical systems. While the efficiency of natural gas combustion sources is more of a formal efficiency adjustment, the efficiency of heat distribution is increased, the reference specific input for fans is reduced, and lighting is reduced very significantly. In the context of the building envelope, the requirement for the heat transfer coefficient for NZEB II is unchanged if compared to the repealed Decree 78/2013 Coll. And, in simplified terms, it is a requirement that tightens the required values of the heat transfer coefficient U (W/m^{2}K) according to the standard ČSN 730540-2:2011 by 30%.

In the area of non-renewable primary energy factors for standard energy carriers, there has been some shift for fossil fuels (from 1.1 to 1.0) and electricity (from 3.0 to 2.6). There have been significant adjustments to the conversion factors for heat from district heating systems. The factors are generally declared as statistically determined at national level according to the energy mix and production efficiency, including the share of renewables.

Perhaps the most significant change brought by the new decree is a significant reduction in the benchmark for non-renewable primary energy demand from 2022 (NZEB II), based on the specific heating demand of the reference building (see **Table 11**). The non-renewable primary energy demand thus becomes a key requirement of the expressed energy performance of buildings from 2022 onwards, as it includes both a reduction in energy demand (effect of shape and orientation, building design, heat recovery) and an increase in the efficiency of technical systems (source efficiency, duct losses, control) as well as the need to use renewable energy sources. The setting implies that essentially new buildings after 2022 will not be without renewable energy sources.

Table 11. *Reduction of the value of primary energy from non-renewable energy sources set for the reference building NZEB II.*

Specific heat demand for heating the reference building $q_{VYT,R}$ [kWh/(m^2year)]	Lowering the benchmark for primary energy from non-renewable energy sources ΔNPE_R [%]		
	For residential zone		For other than residential zone
	Energy reference area of the building ≤ 120 m^2	Energy reference area of the building > 120 m^2	
≥ 90	50	60	40
80	45	55	
70	40	50	
60	35	45	
50	30	40	
40	25	30	
≤ 30	20	20	

Plus energy building

A Plus energy building means a building with a negative balance of non-renewable primary energy on an annual basis. According to the Czech standard ČSN 73 0540-2, plus energy building is assessed at two levels. Level A includes the non-renewable primary energy consumption for heating, hot water, auxiliary energy for the operation of technical systems and user energy for the operation of electrical appliances and lighting, while Level B includes only heating, hot water and auxiliary energy. Level B is used in the official assessment. User electricity consumption for appliances is not included in the official assessment of the house, although it ultimately has a significant impact on the energy balance of the house, especially when using intermittent renewable electricity sources.

Low energy building

In the Czech Republic, the NZEB standard is much stricter than a low-energy building. The definition of low-energy is given in the informative Annex A to ČSN 73 0540-2. A low-energy building is a house that meets requirements on fresh air ventilation, heating to the desired temperature, and has a specific heating demand of 50 kWh/m^2y or less. The requirements for building envelope airtightness or heat transfer coefficient are only recommended.

4.1.2. THE CASE STUDY IN KARVINA

Description of renovation

The building is four-storey, with a basement, and having five tracts. The area of the typical floor is about 1850 m^2. In the basement, there is a hospital pharmacy area, technical facilities of the building, workshops, and a food dispensing room. The house is connected to the district heating system. A heat transfer station is installed in the building, which prepares heat for heating and domestic hot water (DHW). The installed capacity is 2 x 550 kW for heating and 475 kW for DHW preparation. The DHW preparation includes a storage tank with a capacity of 1500 l, in which it is possible to heat the DHW in the event of an accident or maintenance with an electric auxiliary heater with capacity 3 x 7.5 kW. The energy monitoring is at the building level and provides information of energy consumption for electricity and heating. The energy consumption data from 2019 to 2020 are presented in **Figure 6**.

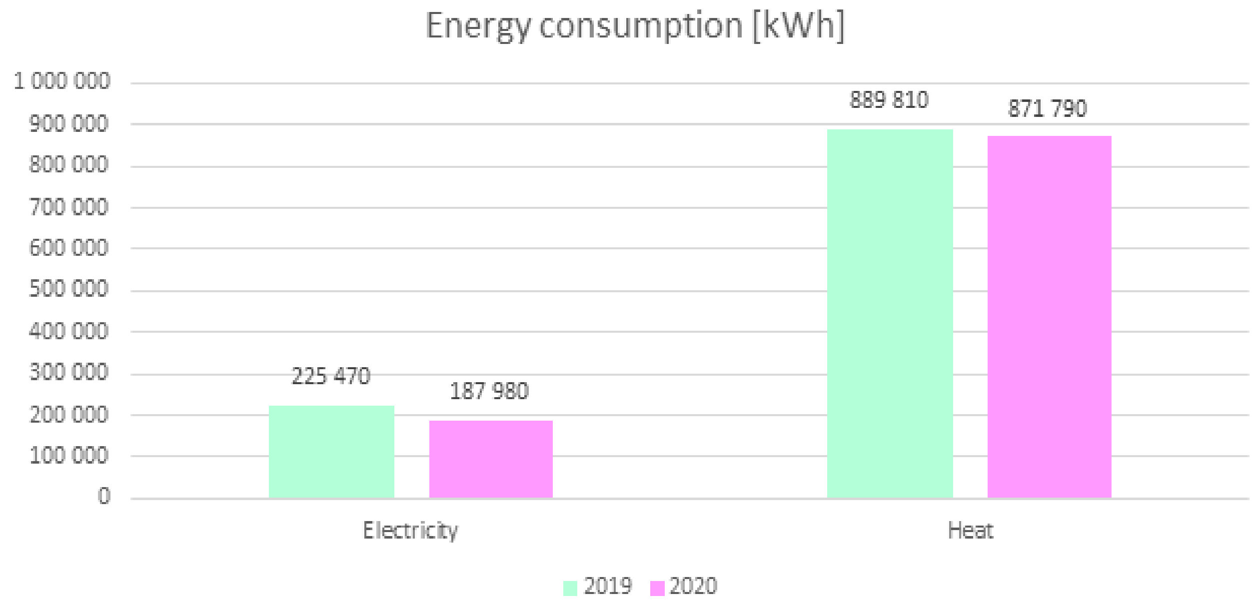


Figure 6. *Monitored building energy consumption [kWh] in 2019 and 2020.*

The health centre refurbishment project was focused on insulation, replacement of windows and replacement of lighting. Individual building standards were evaluated for different energy design scenarios. In the framework of the nZEB and plus building evaluation, the electricity consumption for lighting only (before refurbishment 131.8 MWh/y; after refurbishment 13.6 MWh/y) was considered according to the current legislation. The heat demand of the building was before refurbishment 966.9 MWh and after 367.6 MWh.

Within the ARV project a 39.9 kWp PV power plant will be installed. The installed power of façade installation is 5.05 kWp. The installed power on the roof installation is 29.575 kWp (inclination 15°) and the installed electrical power of the PVT system on the roof is 5.7 kWp (inclination 45°). The expected overall annual electricity production is 34.4 MWh. There are still places available for a further installation of the PV plant on the building and its surroundings to achieve the plus energy standard, namely the facade (159.4 kWp) and the carport (200 kWp). For the evaluation of different building energy standards, the following scenarios were considered:

1. Building before refurbishment, connected to district heating (coal heating plant).
2. Building after refurbishment, connected to district heating (coal heating plant).
3. Building after refurbishment, connected to district heating (coal heating plant), PV installation within ARV project (39.9 kWp).
4. Building after refurbishment, connected to district heating (biomass heating plant), PV installation within ARV project (39.9 kWp).
5. Building after refurbishment, decentralized air to water heat pump, PV installation within ARV project (39.9 kWp).

According to the **Table 12**, it can be seen that the existing refurbishment, including the installation of the PV plant within the ARV project (scenario 3), meets the original NZEB I and the more stringent version of NZEB II valid since 2022. In order to achieve the standard of an energy plus building, it would be necessary to either install a PV plant on the façade (159.4 kWp) and carport (150 kWp) or change the source base to district heating to biomass and install 51 kWp on the façade. The replacement of the source base for biomass and waste combustion is planned by the district heating operator for the near future.

Table 12. *Indication of the achievement of each standard (by colour) with an indication of how many more PV power plants would need to be installed.*

Scenario	nZEB I (before 2022)	nZEB II (after 2022)	Plus energy building
1	x	x	x
2	🟩	x	x
3	🟩	🟩	159.4 kWp + 150 kWp carport
4	🟩	🟩	51 kWp façade
5	🟩	🟩	159.4 kWp + 200 kWp carport

4.1.3. METHODOLOGY

The methodology followed for conducting a Life Cycle Assessment (LCA) adheres to the latest standards in building LCA, as referenced in previous sections (e.g., EN 15978, EN 15804). This study aims at analysing the environmental impacts associated with the refurbishment of the Karvina Health Centre once it reaches the NZEB standard.

The assessment is performed considering the “cradle-to-cradle” approach, encompassing the construction phase (modules A1-A4), replacement of building components (module B4), operational energy use (module B6), end-of-life (modules C2-C3), and benefits (module D). **Table 13** shows the life cycle modules considered. To model module B4, service lives of 35 years for windows, 50 years for insulation materials, 25 years for wall linings, 10 years for wall coverings, 20 years for building services, 25 years for PV panels, and 10 years for batteries are considered. Module B6 addresses impacts linked to operational building energy use for heating with data derived from preliminary energy simulations. The PV production is considered in module D.
Results are aggregated in:

- Embodied impacts (modules A1-A4)
- Embodied recurring impacts (module B4-B5)
- Operational impacts (module B6)
- End-of-life impacts (modules C2-C3)
- Benefits achievable (module D)

Nevertheless, since it is a renovation, only the new materials needed for the refurbishment have been considered for the assessment, following a burden-free approach; this means that the materials inherited from the existing building do not account for any maintenance or waste produced at the end of their life cycle; waste generated during construction works is, instead, considered.

Bills of material quantities for the health centre were gathered by extracting data from a digital twin modelled through a BIM software which organized them by categories and classes. Additionally, MS Excel datasheets from construction developers were utilized in the collection process. Both approaches require the model to contain as many details as possible to facilitate a systematic mapping process and to reduce the number of approximations due to estimation. Indeed, the main output from this phase is the Bill of Quantities (BoQ) which is then used as an input for the environmental assessment. One Click LCA serves as the primary background database for LCA modelling, which accounts for Environmental Products Declarations (EPDs) in accordance with the EN 15804 + A1 standard. One Click LCA facilitates the importation of Excel files through a specific template that necessitates the inclusion of specific data elements, including class, IFC material, thickness, quantity, unit, comments, and other details that are not pertinent to our study. The term 'class' refers to the building components, such as “Foundations and Substructure” or “Vertical Structures and Façade”, providing clarity on the most impactful building part. In the IFC material section, the inclusion of BoQ items is needed, allowing the LCA software, utilizing keywords, to potentially automate the identification of the most suitable EPD. It is noteworthy that each EPD is available in varying units (e.g., m^2, m^3, kg), underscoring the importance of providing comprehensive information for seamless conversion to alternative units, if required. The expected life cycle of the refurbished complex for calculation purposes was fixed at 50 years, which is also the reference study time indicated in Level(s) indicator 1.2: Life cycle Global Warming Potential. The functional unit considered for the assessment is the heated floor area of the Centre, measured in square meters [m^2].

Table 13. *Life cycle modules considered.*

LCA module	Description	Included
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	x
B1	Use	x
B2	Maintenance	x
B3	Repair	x
B4	Replacement	✓
B5	Refurbishment	x
B6	Operational energy use	✓
B7	Operational water use	x
C1	Demolition, de-construction	x
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	✓
	Renewable energy production	✓
	Biogenic carbon	✓

The file designated for import into One Click LCA was meticulously prepared, referencing an internal database previously developed and based on One Click LCA, albeit with EPDs reflecting the highest CO_2 emissions in the Czech market. Datasets were carefully chosen, with a primary consideration given to Czechia and neighbouring countries, accounting for their electricity emission factors—predominantly favouring Germany, Italy, and Poland. For LCA modules A4 and C2, computations were conducted directly within One Click LCA, factoring in transportation and the distance between the manufacturing and construction sites based on standard regional values for the specific product type. Transportation considerations were also revisited in modules B4-B5 (replacement). An additional salient consideration is the potential variability of EPDs among distinct life cycle inventory databases (LCI).

It is imperative to emphasize that the EPDs selected for this assessment do not usually pertain to the specific products utilized in the refurbishment; instead, they align with the same typology and materiality. There exists the possibility that the materials employed in the refurbishment may exhibit a more favourable environmental impact than the selected EPDs. Therefore, if the assessment yields satisfactory results with scarcely environmentally friendly products, it implies that superior outcomes can be attained with the actual installed products. However, the pursuit of specific EPDs must be undertaken to align with the utmost accuracy and proximity to real implemented products.

4.1.4. LCA REFURBISHMENT RESULTS

Figure 7 shows an overview of the LCA phases and their weightings which resulted from the application of the above-mentioned methodology. The embodied impacts (modules A1-A4) accounted for 15% of the total - 1.52 kg CO_2-eq/m^2y (**Figure 8**). Under the hypothesis done, namely that the sourcing of building materials is mostly local (or from neighbouring countries), the impacts and energy uses attributable to the transportation to the construction site (module A4) are quite negligible. On the contrary, module B4 made a substantial contribution (15%) due to the necessity of substituting windows and energy systems during the building life cycle, which were the main elements of the refurbishment. The emissions linked to the operational stage constituted the 67% of the total. In contrast, the contribution of end-of-life emissions resulted the lowest one with a 2% of the total.

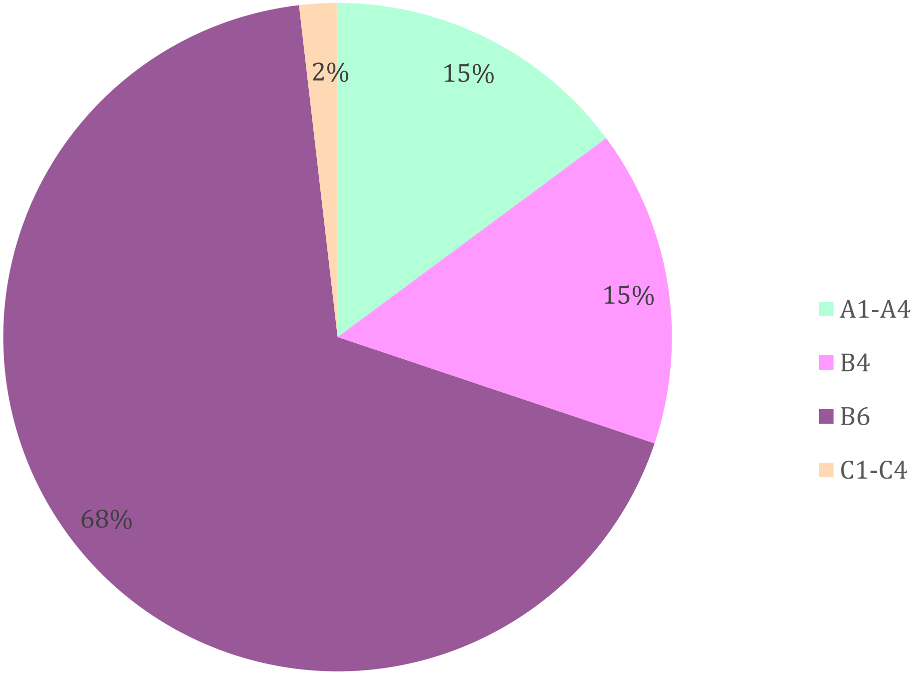


Figure 7. Share of the different life cycle stages in the 'Cradle to Gate' GWP of the Karvina Health Centre refurbishment (module D is excluded).

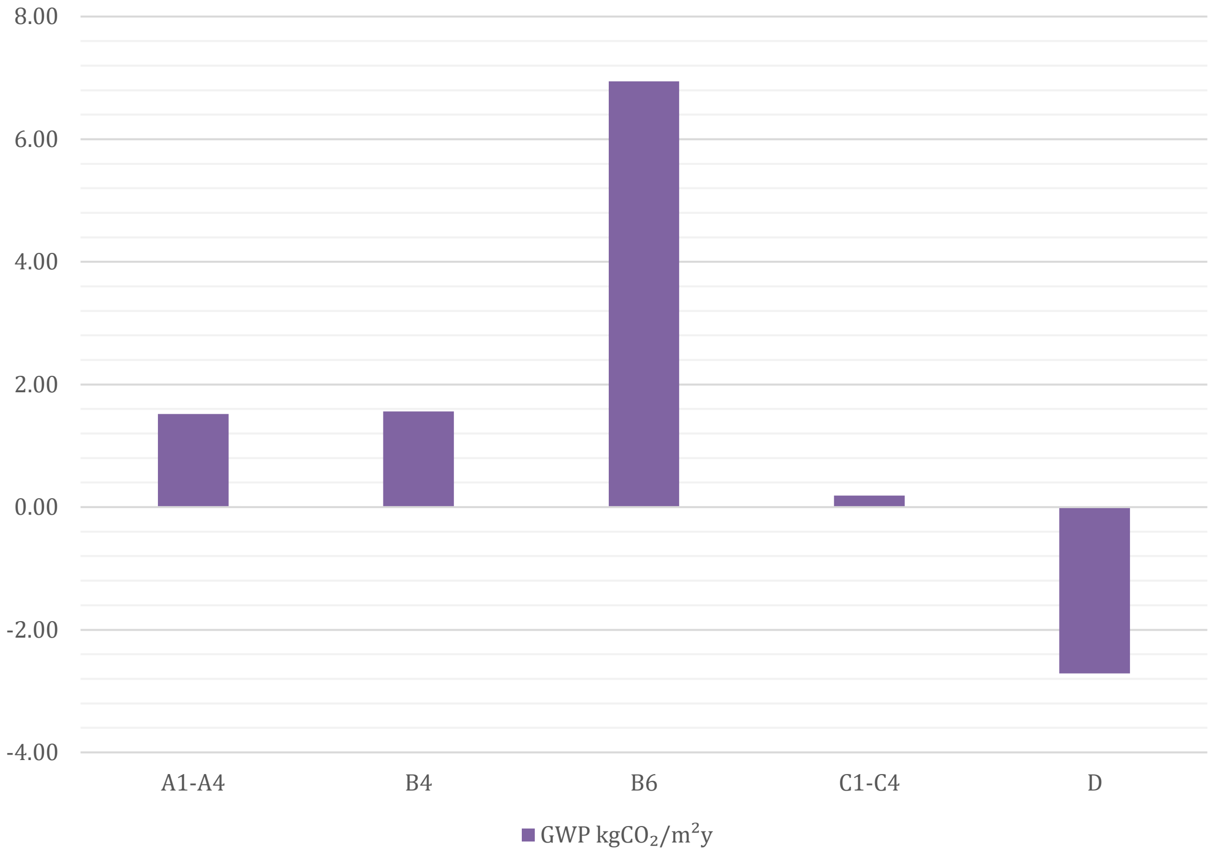


Figure 8. *Life cycle global warming potential for the refurbishment of the Karvina Health Centre.*

The operational energy calculations were executed utilizing Energie 2023, a widely employed simulation tool in the Czech Republic, in accordance with Czech legislation. Subsequently, the outcomes for heating and DHW production were integrated into One Click LCA to ascertain the operational carbon footprint (kg CO_2e) –The cumulative result is 6.94 kg CO_2e/m^{2}y, representing approximately 70% of the total impacts incurred to date (**Table 14**)– this is mostly due to the district heating which accounts for 367.6 MWh/y.

Table 14*. LCA preliminary results.*

Category	**Result**
Overall impacts	10.33 kgCO_2e/m^{2}y
Operational impacts	6.94 kgCO_2e/m^{2}y

Figure 9 illustrates the comprehensive assessment of CO_2 emissions attributed to various building parts in accordance with Level(s) indicator 1.2: Life cycle Global Warming Potential. The most influential part of the building is its structure, encompassing walls and floors. The refurbishment efforts have primarily focused on replacing the façade and retrofitting the roof. Regarding services, the second most impactful aspect of the building emerged from the assessment, PV panels and other advanced building technologies were taken into account. In this figure, however, B6 phase is not considered.

LCC applications were not found in the submitted deliverable.

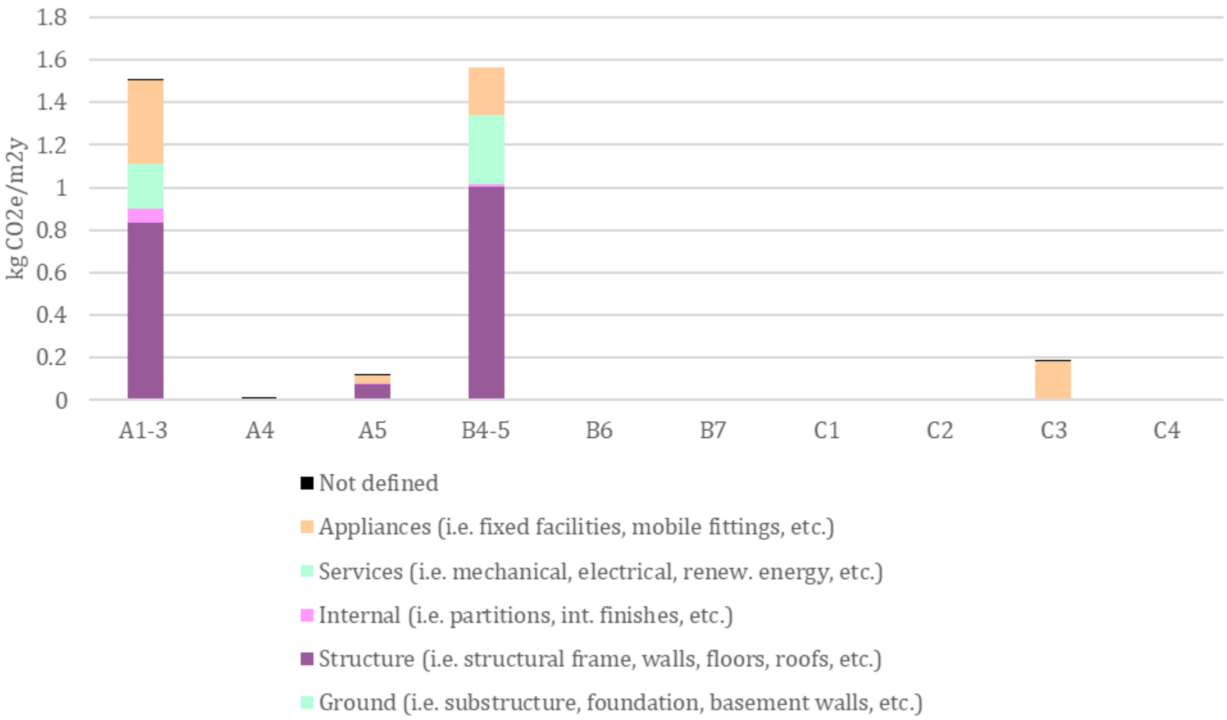


Figure 9. *GWP over the life cycle stages per building parts in compliance with Level(s) for the refurbishment of the Karvina Health Centre*

A comparison of the energy-related emissions (expressed in $kgCO_2e/m^2y$) before and after the renovation is illustrated in **Figure 10**. Specifically, the energy demand for heating and DHW production (B6 module) amounted to 966.9 MWh per year before the renovation, which subsequently decreased to 367.6 MWh per year after the renovation. This resulted in energy-related emissions of 18.26 $kgCO_2e/m^2y$ and 6.94 $kgCO_2e/m^2y$, respectively. Consequently, the energy-related emission levels for the renovated status were nearly three times lower than those observed before the renovation.

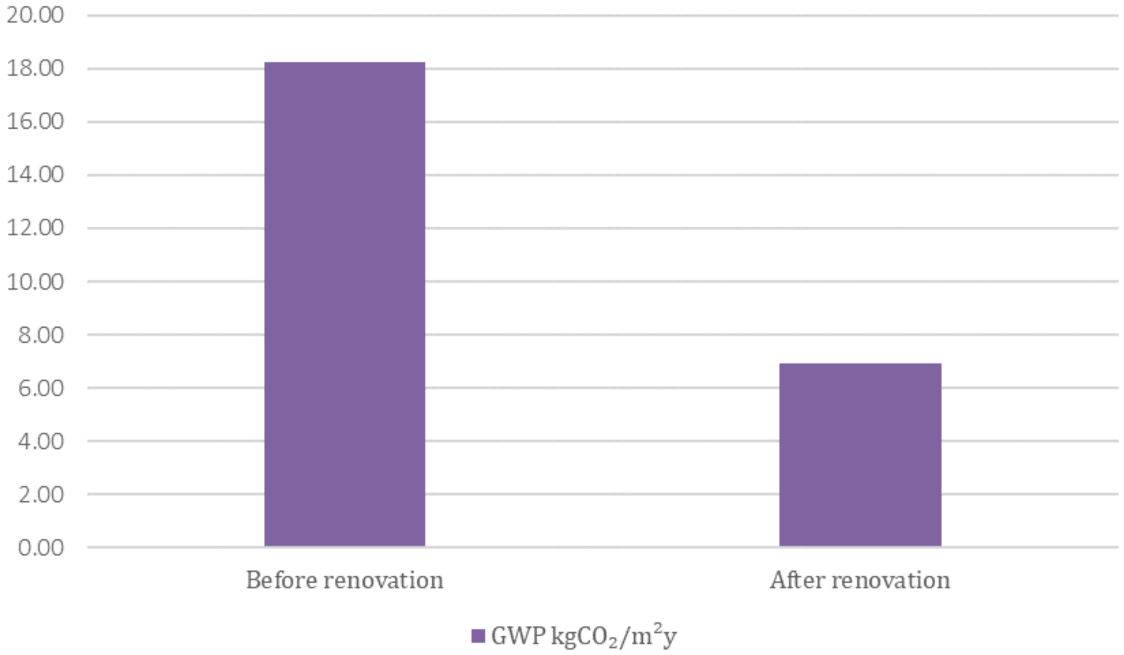


Figure 10. *Energy-related emissions (B6 module – annual energy consumption) before and after the renovation.*

4.2. OSLO DEMO

The ARV demo in Oslo is Voldsløkka skole and Cultural Area, consisting of a new building (S-building) and a renovated building (H-building). The project was completed in 2023 and is Norway's first plus-energy school. The renovated building reaches energy class B, an ambitious target for a renovation project. The set of actions that undertaken by the ARV project includes resource efficient renovation processes, district energy analysis and operation, and highlights social, educational, and digital aspects to enhance citizens involvement and generating Citizen Energy Communities. The design process and related calculations are reported in ARV report D4.1 Design guidelines for a climate positive circular community in Oslo.

For ambitious projects that set targets for life cycle calculations, (nearly) zero energy or zero-emission ambitions, the client and project team (often based on a certification scheme like FutureBuilt nZEB or FutureBuilt Plusshus) may define which assumptions are to be used for energy calculations to test that the design meets these ambitions. These calculations come in addition to what is required in the Norwegian building code (TEK17).

According to TEK17, building energy evaluation of non-residential buildings has to be performed according to two criteria:

- Compliance with energy frame method (chapter 14.2.1)
- Compliance with realistic assumptions (chapter 14.2.5)

In addition to the two criteria described above, additional obligatory energy labelling and the Plusshus scheme (if the building is a plus energy) are needed.

4.2.1. NZEB, PEB, LOW-E BUILDINGS: DEFINITIONS

4.2.1.1 Building energy evaluation to comply with the energy frame method (TEK17 § 14-2-1)

Building energy evaluations for building code compliance are performed with NS-3031:2014, which defines normative values for operational schedules for internal heat gains and electricity use for lighting, equipment, hot water heating, set points for space heating and cooling, as well as standard ventilation rates. These inputs are determined according to the building type and differ for operating hours between occupied and unoccupied times (e.g., nights and weekends), as in Appendix A in NS3031:2014.

According to this calculation, the Voldsløkka project (S-building and H-building) is well within the energy frame requirement of 110 kWh/m^2 for school buildings and 130 kWh/m^2 for cultural buildings (as shown in **Table 15**). From the provided models, the calculated net energy demand is 59 kWh/m^2 for the new building (S-building) and 117 kWh/m^2 for the renovated building (H-building).

To ensure an acceptable quality for selected building components (on average), certain minimum performance criteria also need to be met (as shown in **Table 16**). Note that for measures in existing buildings, the municipality may, upon request, grant full or partial exemptions from technical requirements if it is considered reasonable.

According to the verification of the minimum performance criteria, the Voldsløkka project is well within the given limits, with the exception of the average U-value of external walls in the H-building.

4.2.1.2. Building energy calculation based on realistic assumptions (TEK17 § 14-2-5)

In addition to the compliance check, an energy calculation in the local climate, based on more realistic assumptions is required for non-residential buildings. The goal of calculating an energy budget is to provide the building owner and users with a good estimate of the expected energy consumption, and an as-built energy budget must be available upon completion and be included in the building's documentation. However, the guideline to TEK17 recommends presenting the most realistic energy budget for the building as early as possible in the planning process to provide a solid foundation for assessing the cost-effectiveness of alternative solutions and optimizing the building energy performance.

Table 15. *Verification of net energy demand according to energy frame method (§ 14-2 Krav til energieffektivitet).*

Description	New S-building	Renovated H-building	Unit
Space heating	11.6	57.7	kWh/m^2
Ventilation heating	5.9	12.1	kWh/m^2
Hot water heating	10.1	10.0	kWh/m^2
Fans	4.5	10.2	kWh/m^2
Pumps	0.5	2.2	kWh/m^2
Lighting	8.0	11.8	kWh/m^2
Equipment	13.3	2.9	kWh/m^2
Space cooling	1.1	0.0	kWh/m^2
Ventilation cooling	4.0	9.9	kWh/m^2
Total net energy use	58.9	116.9	kWh/m^2
Legal requirement for building category;	*School building*	*Cultural building*	
	110.0	*130.0*	*kWh/m^2*

Table 16. *Verification of minimum requirements in the building code (§ 14-3 Minimumsnivå for energieffektivitet).*

Description	New S-building	Renovated H-building	Minimum	Unit
U-value external walls	0.17	0.28	0.22	W/m^{2}K
U-value exterior roofs	0.10	0.13	0.18	W/m^{2}K
U-value exterior floors	0.11	0.13	0.18	W/m^{2}K
U-value glass/windows/doors	0.8	0.8	1.2	W/m^{2}K
Envelope air tightness (50 Pa)	0.3	0.7	1.5	per hour

To form the realistic energy budget, all building technical specifications from NS3031:2014 are to be presented, such as:

- U-value external walls, roofs, floors, openings
- Envelope air tightness at 50 Pa
- Thermal bridges values

- Heat recovery efficiency of Air Handling Units
- Specific fan power of Air Handling Units
- Installed lighting power
- Ratio of coverage of space heating, air handling unit, and domestic hot water to be supplied by the energy systems (e.g. heat pump, district heating, etc)

In addition to the above, energy use in unheated areas, outdoor consumption for snow melting systems and lighting, as well as energy use for data servers and other industrial equipment have to be included. Calculations can be based on the supplied (purchased) energy at the calculation point. Real system efficiencies for heating and cooling systems are to be used.

4.2.1.3. Building energy performance certificate

Energy labelling of buildings generally follows the same procedure and input values from NS 3031, but the ventilation rates are to be based on the actual design ventilation rates (or alternatively to be based on standard normative ventilation rates if these are higher than the design, or not available, which sometimes is the case in existing buildings). The calculations are to be performed in a standard reference climate and local climate, which in terms of location are the same in this case (Oslo).

For the project, the energy labelling calculations are presented below:

- **A label** is assigned to the new S-building with geothermal heat pumps specified to cover 98 % of the heating demand for rooms and ventilation and 100 % of hot water demand.
- **B label** is assigned to the renovated H-building, based on the assumptions the heating demand for rooms and ventilation is covered by district heating while heat pumps provide hot water heating.

In both cases, ventilation, and space cooling (in the parts of the school where space cooling is installed) are covered by heat pumps and free cooling. Note that the setpoint for space cooling is set to 25 °C which differs from the building code compliance, which specifies a setpoint of 22 °C. This, together with design ventilation rates, leads to a difference between the calculated demand presented in the TEK17 code and the demand used as input to the delivered energy calculation (shown below in **Table 17**).

Table 17. *Energy labelling calculations.*

Description	New S-building	Renovated H-building	Unit
Delivered energy use	35	109	kWh/m^2
Obtained energy label	A (<=75)	B (<=135)	kWh/m^2
for building category:	*School building*	*Cultural building*	

Plus-energy evaluation (FutureBuilt's old Plusshus definition)

FutureBuilt defines Plusshus as a "house that produces more energy than it consumes" with an annual surplus in operation of 2 kWh/m^2. The first versions of the definition (issued in 2014) opened for excluding electric energy use for equipment (e.g. plug loads) from the system boundary, thus making it easier to reach the target.

In order to document the energy balance in the design phase, normative schedules according to NS3031:2014 are to be used together with the actual design ventilation rates (similar requirements given for the energy labelling, as seen above). In contrast to the energy labelling scheme, the delivered energy to the building is not used directly but is weighted according to the energy carrier (1.0 for electricity and 0.43 for district heating).

To reach the required plus energy target, the use of an onsite photovoltaic system is needed. The estimated electricity production from the PV system installed in the S-building is ca. 230000 kWh/year which, when divided by the S-buildings floor area, amounts to 24.8 kWh/m^2 year from PV.

Table 18 shows the sum of delivered energy with or without weighting factors and with or without including electricity use for equipment. By excluding energy use for equipment, the S-building designs' annual surplus reaches the Plusshus criteria when the energy production from PV is factored in.

Table 18. *Calculated delivered energy and weighted delivered energy.*

Description	S-building	H-building	Factor	S-building	H-building	Unit
Electricity	34.6	30.9	1.00	34.6	30.9	kWh/m^2
District heating	0.4	78.3	0.43	0.2	33.7	kWh/m^2
PV el. production	-24.8	-	1.00	-24.8	-	kWh/m^2
Sum	**35.0**	**109.2**		**34.8**	**64.6**	**kWh/m^2**
Sum + PV	**10.2**	**109.2**		**10.0**	**64.6**	**kWh/m^2**
Sum excl. equipment	**21.7**	**106.3**		**21.5**	**61.7**	**kWh/m^2**
Sum excl. equipment + PV	**-3.1**	**106.3**		**-3.3**	**61.7**	**kWh/m^2**

Another more recent scheme that excludes equipment from the assessment boundary is the NZEB criteria of KDD (2023), proposed as part of the work that is still undergoing to align Norwegian legislation with EPBD-II (2010) and the European taxonomy. According to KDD's definition, both buildings fulfil the requirements that are calculated from delivered energy (or more precisely with political weighting factors of 1.00 for all energy carriers). However, this is hardly surprising as the proposal cannot be viewed as a strengthening of current regulations. Besides KDD's NZEB guidelines are considerably less ambitious than the NZEB criteria that projects using Futurebuilt v2.0 (2023) criteria must meet.

4.2.1.5. Scenarios for the streamlined analysis

Based on the above-described calculation methods and the peculiar combination of a new plus-energy school building with the renovation of an old cement factory in the Oslo demonstration project, the following scenarios have been developed:

- New school building (S-building):
    - Reference scenario (minimal upgrade of TEK17 requirements)
    - First upgrading step (NZEB level)
    - Second upgrading step (plus-energy building, as built)
- Renovated cement factory to cultural building (H-building):
    - Reference scenario (renovated building, as built)
    - First upgrading step (TEK17)

4.2.2. S-BUILDING AND H-BUILDING ENERGY SCENARIOS

S-building

The starting reference scenario of the S-building is defined on a small upgrade of the TEK17 minimum requirements. Two upgrading steps are developed to reach the actual plus-energy building. The upgrading steps are based on improving the insulation performance of the building envelope (1st upgrading step) and thereafter on adding photovoltaic panels to reach the required plus-energy target. **Table 19** shows the technical specifications of the building in the above mentioned three scenarios.

As shown in **Table 19**, the reference scenario differs from the minimum requirements set in the TEK 17 (**Table 16**) according to the considerations described as follows:

- With regards to the external walls, the U-value of wood frame constructions is reduced to what can be expected with 200-mm- thick insulation. The walls made of concrete and those laying below ground are

left unchanged. The wall insulation thickness has been reduced to the minimum requirement of the building code (0.22 W/m²K which equals ca. 200 mm insulation in a standard wood frame wall), as slimmer walls generally allow a simple construction process and less lost floor space. However, the thermal bridge value may also be impacted, especially for structures with aluminium or concrete load-bearing systems.
- With regards to floors, insulation thickness is assumed to be reduced by 50 mm everywhere.
- With regards to roofs, it is assumed to reduce the insulation thickness to 300 mm on average, except for those roof sections that have already this insulation thickness or a lower one for technical reasons.
- With regards to windows, glass facades and doors, no changes are made. However, potential cost savings can be realized by opting for 2-layer glazing instead of 3-layer glazing, as long as it meets the minimum requirements, especially when this choice facilitates easier installation (less weight may lead to less workforce and equipment needed for the installation).

Table 19. *Summary of technical specifications of S-building across the three scenarios.*

S-building component	Reference scenario	NZEB level	Plus-energy	Unit
U-value external walls	0.22	0.17	0.17	W/m²K
U-value exterior roofs	0.13	0.10	0.10	W/m²K
U-value exterior floors	0.14	0.11	0.11	W/m²K
U-value glass/windows/doors	0.80	0.80	0.80	W/m²K
Envelope air tightness (50 Pa)	1.0	0.3	0.3	per hour
Thermal bridge value	0.05	0.03	0.03	W/m²K
Heat recovery efficiency AHU	88	88	88	%
Specific fan power AHU	0.62	0.62	0.62	kW/m³/s
Lighting power in operation	3.56	3.56	3.56	W/m²
Space heating covered by	98% GSHP (SCOP~3.2)	98% GSHP (SCOP~3.2)	98% GSHP (SCOP~3.2)	-
AHU heating covered by	98% GSHP (SCOP~3.6)	98% GSHP (SCOP~3.6)	98% GSHP (SCOP~3.6)	-
DHW heating covered by	GSHP (SCOP~3.5)	GSHP (SCOP~3.5)	GSHP (SCOP~3.5)	-
Photovoltaic installation	None	None	24.8	kWh/m²y

Table 20 below summarizes the changes to the building envelope made to reach the reference scenario.

H-building

As described above, the starting point (reference scenario) of the H-building is the existing status of the renovated building as a cultural centre. It was not possible to compare the renovated status of the H-building with its previous use, as the building was a cement factory. It was decided, therefore, to refer the energy calculations to the requirements given for cultural buildings. The reference scenario of the H-building is then upgraded to a NZEB level. It must be noted that the H-building is considered a protected building with historical value. This led to the decision of insulating the building on the inside to maintain the appearance of the original façade. In the upgraded scenario, proposed here, the insulation has to be necessarily placed on the outside of the building façade, to reach the proposed insulation level. **Table 21** below summarizes the variation of the technical specifications of the building throughout the two scenarios. It is worth comparing the values here to the minimum requirement set in the TEK17 and described in **Table 16**.

Table 20. *Technical specifications of the downgrading of the existing building components in the S-building.*

Wall type	Location	Area [m^2]	U-value [W/m^{2}K]	Eq. U-value	U-value [W/m^{2}K]	Eq. U-value	Description
Wood frame	Any	2759	0.15	0.15	0.21	0.21	reduce to 200 mm
Basement	Teaching	449	0.21	0.15	0.21	0.15	unchanged
Concrete	Teaching	510	0.32	0.32	0.32	0.32	unchanged
Sum/mean		3719		0.17		0.22	

Floor type	Location	Area [m^2]	U-value [W/m^{2}K]	Eq. U-value	U-value [W/m^{2}K]	Eq. U-value	Description
Basement floor	plan U	778	0.06	0.05	0.09	0.07	50 mm less
Exposed floor	plan 2	429	0.17	0.17	0.23	0.23	50 mm less
Floor on ground	plan 1	1040	0.22	0.13	0.33	0.16	50 mm less
Sum/mean		2247		0.11		0.14	

Roof type	Zone	Area [m^2]	U-value [W/m^{2}K]	U-value [W/m^{2}K]	Description
Flat plan 5	Teaching	917	0.08	0.13	200 mm less
Flat plan 4	Teaching/Staff	749	0.10	0.13	100 mm less
Sloped (bridge)	Teaching	193	0.11	0.13	75 mm less
Flatt roof plan 5	Teaching	361	0.13	0.13	unchanged
Flatt roof plan U	Entrance	20	0.17	0.17	unchanged
Sum/mean		2240	0.10	0.13	

Window/glass/door type	Zone	Area [m^2]	U-value [W/m^{2}K]	U-value [W/m^{2}K]	Description
Windows in wood frame walls	Any	888	0.80	0.80	unchanged
Windows in concrete walls	Any	50	0.80	0.80	unchanged
Glass facades	Any	340	0.80	0.80	unchanged
Door	Teaching	3	0.80	0.80	unchanged
Sum/mean		1281	0.80	0.80	

The technical specifications given in the upgraded scenario of the H-building are calculated according to the following considerations:

- With regards to external walls, the U-value of the main facades is improved to what can be expected with an exterior insulation system like RedAir with a 300-350-mm total insulation thickness. Other walls are left unchanged.
- With regards to floors, no changes are envisioned, and the current level is equivalent to ca. 150 mm of insulation.
- Roofs may be much easier to insulate than the floors, so the insulation thickness is increased up to 450 mm.
- With regards to windows and doors, no changes are proposed.

Table 21. *Summary of technical specifications of H-building across the two scenarios*

Description	Reference scenario	NZEB level	Unit
U-value external walls	0.28	0.15	W/m^{2}K
U-value exterior roofs	0.13	0.09	W/m^{2}K
U-value exterior floors	0.13	0.13	W/m^{2}K
U-value glass/windows/doors	0.80	0.80	W/m^{2}K
Envelope air tightness (50 Pa)	0.74	0.60	per hour
Thermal bridge value	0.05	0.03	W/m^{2}K
Heat recovery efficiency AHU	83	83	%
Specific fan power AHU	1.50	1.50	kW/m^3/s
Lighting power in operation	4.07	4.07	W/m^2
Space heating covered by	100% DH (~0.9)	100% DH (~0.9)	-
AHU heating covered by	100% DH (~0.9)	100% DH (~0.9)	-
DHW heating covered by	100% HP (SCOP~5.2)	100% HP (SCOP~5.2)	-

Table 22. *Technical specifications of the upgrading of the existing building components in the H-building.*

Wall type	Location	Area [m^2]	U-value [W/m^{2}K]	U-value [W/m^{2}K]	Description
Wall N towards room	North	26	0.1	0.10	unchanged
Wall roof patch	Axis 26	449	0.16	0.21	unchanged
Wall E towards room	East	21	0.17	0.32	unchanged
Facades	Any	977	0.30	0.14	300 or 350 mm insulation
Wall roof patch	Axis T	29	0.33	0.33	unchanged
Sum/mean		1502	0.28	0.15	

Floor type	Location	Area [m^2]	U-value [W/m^{2}K]	Eq. U-value	U-value [W/m^{2}K]	Eq. U-value	Description
Floor on ground	Any	1672	0.23	0.13	0.23	0.13	unchanged

Roof type	Location	Area [m^2]	U-value [W/m^{2}K]	U-value [W/m^{2}K]	Description
Roof surfaces	Any	1735	0.13	0.09	150 mm more (450 mm)

Name	Location	Area [m^2]	U-value [W/m^{2}K]	U-value [W/m^{2}K]	Description
Windows in facades	Any	280	0.75	0.75	unchanged
Skylights	Any	3	0.80	0.80	unchanged
Doors, facades	Any	80	0.94	0.94	unchanged
Door, inntaksrom	Any	2.13	1.20	1.20	unchanged
Sum/mean		362	0.79	0.79	

Table 22 summarizes the calculations done to achieve the technical specifications in the upgraded scenario of the H-building.

General considerations

The proposed changes have been done in consideration of what is possible and sought after to quantify the LCA and LCC calculations. Therefore, the changes that impact the energy results but cannot be estimated in terms of materials or costs are left out, as follows:

- The cost of improved ventilation heat recovery efficiency is negligible and therefore not considered in the scenarios.
- The project ventilation design uses very low specific fan power (SFP = 0.62 kW/m^3/s), compared with more typical values (of 1.2 – 1.5 kW/m^3/s). A lower SFP can be usually achieved by larger duct dimensions, considering the length of ducts, the number of duct bends, and the use of demand-controlled valves. To assess such alternatives in terms of the required space, cost and materials, a detailed design for the ventilation system would have to be developed which could influence the overall design of the building. Therefore, the SFP values have been left unchanged in the scenarios.
- Thermal bridging effects are not directly correlated to the insulation level. The value of 0.05 W/K m^2 is proposed in the reference scenario because it is the value to be provided for wooden buildings if no calculation is made.
- The reference value of 10 W/m^2 for the installed lighting power in schools must be used if documentation is not provided. However, this value was set in an era before LED lights became commonplace. Alternatively, without an assessment, a simple 20% reduction of reference values (equal to 8 W/m^2) is accepted if the building has an automatic control system. By considering the large use of LED installations and the automatic control system based on occupancy schedules and sensors, the proposed value is set down to 3.56 W/m^2.
- Additional costs due to improvements in envelope air tightness are difficult to calculate. However, the additional working hours for the construction details and testing can be estimated.
- The Ground Source Heat Pump (GSHP) is a large contributor to lower the delivered energy. When the building envelope is downgraded, which leads to increased heating needs, the peak power also increases which may lead to a greater reliance on the secondary heating carrier (district heating which today is estimated to only be necessary to cover 2% of total demand). The required temperature levels for any radiator/convector heating circuits may also increase, which may reduce the SCOP of certain HPs. A greater heating demand may also require a larger installation (larger boreholes, bigger heat pump units, or more heat emitter capacity in the space heating system which of course comes at a cost).

4.2.3. LCA AND LCC METHODOLOGY

This section aims to describe the methods behind the application of streamlined LCA and LCC in the Oslo Demo project. The analysis was done simulating a design process answering the question about economic / ecological feasibility of different scenarios. The scenarios defined in chapter 4.2.1.5 are used for comparing alternative solutions for both S-building and H-building, in terms of embedded and operational emissions, and costs. For the sake of simplicity, limited boundaries related to both spatial and temporal systems are selected as below:

Table 23. *reference scenario of the spatial system boundary in both buildings for the streamlined LCA+LCC analysis*

Building	**Wall**	**Roof**	**Floor**	**PV panels**
	Current insulation thickness (mm)	Current insulation thickness (mm)	Current insulation thickness (mm)	Area (m^2)
S - Building	200	300	50	0
H- Building	100 (interior)	300	-	-

4.2.3.1. Spatial system boundary

In the scenarios related to the S-building, the spatial system boundary is limited to insulation on the building skin (roof, floor, and exterior walls), and the presence of PV panels on the roof. In the H-building, improvements have been analysed concerning the insulation on exterior walls and roof only. **Table 23** lists the base case values (reference scenario) of these elements.

The added insulation thicknesses and amount of added PV panels were defined by the energy calculations for the scenarios. Because of the H-building's historical value, an exterior insulation would not be possible. We considered it nevertheless to analyse the implications of such a scenario on emissions and costs. The changes (in comparison to the reference scenarios) are shown in **Table 24** with their related unit costs and emissions. The corresponding materials are mineral wool for the walls, XPS for the roof, and EPS for the floor.

Table 24. *Scenarios, unit costs and unit emissions (see also D4.1, chapter 5.4)*

Building	Improvement stage	Wall*			Roof**			Floor***			PV panels****		
		Added insulation thickness [mm]	Unit cost [€/m^2]	Unit emissions [kg CO_2 eq. /m^2]	Added insulation thickness [mm]	Unit cost [€/m^2]	Unit emissions [kg CO_2 eq. /m^2]	Added insulation thickness (mm)	Unit cost[1] [€/m^2]	Unit emissions [kg CO_2 eq. /m^2]	Area [m^2]	Unit cost [€/m^2]	Unit emissions [kg CO_2 eq. /m^2]
S - Building	1st	120	44.66*	3.71	200 100 75	27 16 10.1	22.2 11.1 8.32	50	13.1	3.55		-	
	2nd	Same as 1st improvement									1853	233.1	119
H - Building	1st	300	117.7	9.62	150	21,5	16.65		-			-	

* Isolasjon utenpå bindingsverk med plastholdere, mineralull

** Isolasjon på tak, XPS

*** Isolasjon i gulv på grunn, EPS

**** BAPV - 0,15 kWp pr. m^2. Inkl. montering og innfesting > 100 m^2

4.2.3.2. Temporal system boundary

As illustrated in **Table 25**, the temporal system boundaries used in the streamlined LCC and LCA are limited to the production (A1-A3), the maintenance (B2), the replacement (B4), and the operational energy (B6) phases. In addition, we included the possible embodied emissions related to maintenance activities in LCC, which are not included in the LCA calculation. The reasoning behind this is the potentially high maintenance cost of the PV panels that needs to be accounted for, even though such maintenance activities do not have a high environmental impact.

Table 25. *Temporal system boundary considered in the streamlined LCA and LCC*

LCA module	Description	Included in LCA	Included in LCC
A1	Raw material extraction and processing	✓	✓
A2	Transport to the manufacturer	✓	✓
A3	Manufacturing process	✓	✓
A4	Transport to the building site	x	x
A5	Installation in the building site	x	x
B1	Use	x	x
B2	Maintenance	x	✓
B3	Repair	x	x
B4	Replacement	✓	✓
B5	Refurbishment	x	x
B6	Operational energy use	✓	✓
B7	Operational water use	x	x
C1	Demolition, de-construction	x	x
C2	Transport to waste treatment facilities	x	x
C3	Waste processing	x	x
C4	Disposal	x	x
D	Reuse, recovery or recycle potential	x	x
	Renewable energy production	✓	✓
	Biogenic carbon	x	x

To pursue the streamlined LCA and LCC, the following indicators are selected in this study:

- Net present value (NPV): NPV assesses the project's performance across a time horizon while accounting for all costs and revenues at the time of their occurrence and applies a discount rate to attribute a time value at that time (Preciado-Pérez and Fotios, 2017). In this context, NPV of both life cycle costs and benefits regarding the energy savings and generation are calculated and presented in Table 18 and 20 in D4.1 Design guidelines for a climate positive circular community in Oslo.
- Benefit-cost ratio (BCR): BCR is one of the well-known indicators in the economic evaluation of upgrading measures that represents the ratio of the total net present value of benefits to the total net present value of costs. Evaluating the BCR based on NPV and in a long-term horizon is suitable for public projects like the Oslo Demo buildings. The selected benefit is limited to the reduction in the delivered energy by both decreasing the energy saving through insulation and generating electricity through the PV panels. In this approach, the discounting method is employed to have a better understanding of future costs and benefits.
- Carbon mitigation value: considering the streamlined LCA and LCC, carbon mitigation value is a valuable indicator, showing the economic viability of upgrading solutions. This indicator can be calculated as a ratio of carbon reduction achieved by an upgrading measure to the total costs of that

solution. In this project, this indicator is expressed in kg CO_2/€ showing the amount of CO_2 emissions saved per 1€ investment in a measure.

- Carbon payback time: Focusing on the emissions aspect of upgrading measures, carbon payback time is an important indicator representing the time required to pay off the initial embodied emissions invested by those measures. This indicator could show the investors how the selection of measures is environmentally efficient in the building.

All the assumptions related to the discount rate, calculation period, areas and unit costs of improvement measures, the maintenance rate, and the electricity and district heating prices are described in section 5.4, D4.1 Design guidelines for a climate positive circular community in Oslo. Additionally, the values related to the EPD data and the carbon intensity of energy carriers are also explained in the mentioned report.

4.2.4. S-BUILDING AND H-BUILDING RESULTS

The detailed results of the streamlined LCA and LCC are described in ARV report D4.1 design guidelines for a climate positive circular community in Oslo.

The streamlined LCA and LCC calculations highlight the crucial role of energy prices in influencing project profitability, with variations in electricity and district heating prices significantly impacting economic evaluations in both the S-building and H-building scenarios. The initial calculations show that none of the improvement scenarios are economically profitable, i.e., that all have a Benefit-Cost-Ratio (BCR) of lower than 1. For the H-building, this indicates that an additional investment into more insulation on walls and floors compared to the as-built solution would have not paid off in energy savings. For the S-building, however, this implies that the as-built solution did not render an economic profit as compared to a minimum legal standard solution. This last outcome is highly dependent on energy price assumptions. With an increase in the electricity price from 0.10 € per kWh to 0.13 € per kWh, the as-built scenario renders a BCR of 1. If the same insulation standard was considered, but no PV systems (1st upgrading), electricity price would have to raise to 0.2 € per kWh to make this scenario profitable. For the H-building, prices would have to rise to 0.28 € per kWh before added exterior insulation would render a profit within the 60-year study period.

The investment costs were calculated using average data, as it would be the case in a design scenario. Hence, uncertainty in these price assumptions is high and a sensitivity analysis on initial investment costs was conducted. In the analysis, we lowered the assumed prices in steps by 10% to 40%, because a public investor with a big building stock would most likely receive more advantageous offers than the average price. The analysis indicates that a decrease in investment costs improves the BCR across all scenarios, though not surpassing 1 with one exception: the S-building, with high insulation standards and a large PV area, achieves economic profitability with a 10% reduction in initial investment costs.

The chosen 60-year calculation period aligns with Norwegian LCA requirements (Norwegian standard 3720), but significantly influences project profitability; a shorter period could notably decrease the NPV of energy-saving costs.

To analyze the cost effectiveness of emissions reduction, we considered varying emission intensities for electricity and district heating. Emissions from electricity are low in Norway compared to other countries in Europe. At the same time, the Norwegian electricity grid is connected with the European grid, so that average emissions intensities of Norway plus EU28 are taken into account. Under these circumstances, GHG emission payback times are quite short in the S building scenarios, from 12.2 to 18.3 years. The scenario without PV panels has the shortest payback times. Overall, this means that these scenarios save GHG emissions within an 18-year timeframe despite the fact that they are unlikely to be economically profitable. The H-building scenario has a carbon payback time between 32 and 51 years, since more and emissions-intense insulation is added as compared to the baseline scenario. This means that to change the design decision that was taken, to target energy class B instead of new building standard, would have resulted in increased emissions that would have taken long to mitigate.

Comparing the buildings, carbon payback times are relatively shorter in the S-building's improvement stages, emphasizing the significance of lower initial embodied emissions and higher operational emissions savings.

Mitigation values (kg CO_2 saved per unit cost invested) indicate that the 2nd improvement (as-built) renders the highest values, between 1.29 and 1.86 kg CO_2-eq saved per € spent. The 1st improvement (without PV panels) has a lower mitigation value, between 0.94 and 1.32 kg CO_2-eq saved per € spent. The lowest values are displayed by the H-building, between 0.68 and 1.07 kg CO_2-eq saved per € spent. However, even the highest value implies that the cost of saving one ton of carbon would be around 538 €, a much higher value than the current carbon pricing in the EU-ETS (European Union Emission Trading System), which reached a high of around 100 € per ton in 2023.

Considering the results of the cost benefit analysis in relation to mitigation values, the as-built solution for the S-building, with a high energy standard and large PV area, is the only solution that has the potential to render a profit, and it has the highest mitigation value. Carbon payback times are slightly higher than for the scenario without PV panels, but still relatively short. For the H-building, adding insulation on the exterior is not favourable neither in an economic nor in an emissions perspective. As such a solution also compromises the heritage value of the building, it can be excluded as a viable alternative.

4.3. PALMA DEMO

This chapter aims to present the methodology and results obtained for a streamlined LCA applied to the Palma demo for a large multi-family building renovation and to a new social housing building.
A large multifamily building at Carrer de Caracas 1 (**Figure 11**) is the representative building type in the area of Nou Llevant, Palma. It is a 4-storey building, where each floor consists of twelve flats. The building was constructed before 1980, when energy regulations for buildings were very limited. Therefore, buildings from this construction period can be characterised by minimal thermal performance requirements for the building envelope, less efficient cooling and heating systems, older windows and other energy consuming features.

***Figure 11**. Selected building archetype for the renovation: large multifamily building.*

The new construction in Palma demo is represented by a building of 35 dwellings in Fornaris street (**Figure 12**). The project proposes a spatial organization that, combined with a constructive approach, allows for the dwellings with very low energy consumption, a quality living experience and a building integrated into a landscape with architectural value.

***Figure 12**. New construction building.*

The Nearly Zero Energy Building (**NZEB**) ambition level was considered for the renovation case and compared with an existing building. The Plus Energy Building (**PEB**) scenario was not considered in this renovation because it is unlikely to be achieved due to the current state of the building and the lack of space to provide photovoltaic energy. The LCA application for the new construction considered a Plus Energy Building (**PEB**) scenario.

The definitions considered for each ambition level are presented in the section 4.3.1. The LCA methodology followed is described in the section 4.3.2 and the results are presented in the section 4.3.3.

4.3.1. NZEB, PEB, LOW-E BUILDINGS: DEFINITIONS

Nearly zero energy building

A nearly zero energy building (NZEB) has been defined and approved in the Spanish Royal Decree 732/2019, of 20th of December 2019 (Government of Spain, 2019), which aims at modifying the technical construction code for buildings, previously approved by the Royal Decree 314/2006, of 17th of March 2006. Section 2 of the RD 732/2019 declares that “NZEB is defined as a building new or already existing that complies with the requirements established in the document called *DB HE ahorro de energía*”. *DB HE ahorro de energía* is a chapter of the technical construction code mentioned before, which defines energy requirements for buildings.

The energy requirements from the technical construction code are divided into 7 blocks (H0 to H6). All requirements need to be achieved to consider a building as NZEB, either for a new building or for a renovation of an existing building. A summary of each block is presented below. The aspects that are not affecting the study-case buildings for LCA purposes such as, for example, requirements for commercial buildings, have been neglected in this summary.

Table 26. *Summary of the technical requirements for each of the parts of the building according to the Spanish technical construction code for new and renovated buildings.*

Technical requirement	Unit	Limiting values for new buildings	Limiting values for renovated buildings
Non-renewable primary energy consumption (H0)	kWh/m²y	35	68.75
Total primary energy consumption (H0)	kWh/m²y	64.4	92
Features of the thermal envelope (H1)	W/m²K	Walls and floors facing outdoor space: 0.56 Roofs in contact with outdoor space: 0.44 Walls, floors, and roofs in contact with non-residential spaces or the ground: 0.75 Windows and blind spaces: 2.3 Doors with more than 50% transparent surface: 5.7	
Renewable energy generation for DHW (H4)	Percentage of renewable energy powering DHW	70% of renewable consumption for buildings consuming more than 5 000 litres per day 60% of renewable consumption for buildings consuming less than 5 000 litres per day	
	Seasonal Coefficient of performance	2.5 SCOP (or greater) when the heat pump is powered with electricity 1.5 SCOP (or greater) when the heat pump is powered with thermal energy	
Renewable energy power installed (H5)	Power installed (kW)	$P1 = F_{pr;el} * S$ $P2= 0.1 * (0.5*S_c - S_{oc})$	
Minimum of charging infrastructure for electric vehicles (H6)	Number of parking lots with the needed infrastructure installed to connect a charging station	100% of the parking lots	Does not apply in the renovation case

Note: *The values presented are different for each climate zone in Spain. The numbers presented are for B zoning, which is the zone Palma is classified in.*

- **Limitation of the energy consumption (H0).** This limitation is different for new and renovated buildings. The calculations for renovated buildings include the replacement of heating systems and the implementation of insulation layers in the façade and roof. This limitation is set as kWh/m^{2}y and is different in each geographical region in Spain. Palma is classified as climatic zone B, and for this climatic zone the requirements to achieve are presented below:

- **New buildings** should not exceed *35 kWh/m^{2}y* of non-renewable primary energy consumption and *64.4 kWh/m^{2}y* of total primary energy consumption.
- **Renovated buildings** should not exceed *68.75 kWh/m^{2}y* of non-renewable primary energy consumption and *92 kWh/m^{2}y* of total primary energy consumption.

- **Features of the thermal envelope (H1)**. Each part of the building thermal envelope being replaced needs to meet the heat transfer requirements presented in **Table 26**.

In renovated buildings, the individual values for each part of the building might be neglected when the complete performance of the building does not exceed the sum of the values given in **Table 26**.

Additionally, in building retrofitting scenarios where more than 25% of the thermal envelope of the building is being renovated, the heat transfer cannot exceed 0.83 W/m^{2}K in buildings with compactness (the relation between the external surface of the building and the volume) below 1 and 0.90 W/m^{2}K in buildings with compactness above 4. For compactness between 1 and 4 heat transfer value should be obtained by interpolation.

- **Thermal installations (H2)** should comply with the building thermal installations regulatory framework called RITE.
- **Lighting installations (H3)** for new buildings should be designed considering the users' needs and energy efficiency. They should have a control system to adjust the lighting to the real occupation of the building, and a system design that prioritizes using natural lighting. There are no specific numeric parameters for this requirement in residential buildings.

The considerations presented can be neglected for renovated buildings when the building doesn't have a surface above 1 000 m^2.

- **Renewable energy generation for domestic hot water (DHW) (H4)** requirement must be achieved when hot water consumption is more than 100 litres per day, either in new or renovated buildings. DHW needs to be powered with at least 70% of renewable energy, or 60% when the hot water consumption is below 5000 litres per day.

At the same time, the seasonal coefficient of performance (SCOP) of heat pumps for domestic hot water (DHW) and/or pool acclimatisation should not be below 2.5 when it is powered with electricity and 1.5 when it is powered with thermal energy.

- New or renovated buildings with a surface above 1000 m^2 should install a minimum capacity of **renewable energy power (H5)**. This minimum power installed will be defined by the minimum value between the following formulas:

$$\boldsymbol{P1 = F_{pr,el} \cdot S}$$

$$\boldsymbol{P2 = 0.1 \cdot (0.5 \cdot S_c - S_{oc})}$$

Where

$\boldsymbol{F_{pr,el}}$ = 0.005 (for residential buildings).

$\boldsymbol{S}$ - building surface [m^2];

$\boldsymbol{S_c}$ - not walkable roof surface or accessible just for maintenance purposes [m^2];

S_{oc} - not walkable roof surface or surface occupied by thermal energy systems [m²].

- New or renovated buildings with parking lots will provide **a minimum number of charging stations for electric vehicles (H6).** Renovations should achieve these requirements just when interventions change the normal use of the building or directly affect parking space (so this does not affect retrofitting interventions in the Palma demo context).

Plus energy building

There is no definition for plus energy building in the Spanish legislation, so it was decided to stick to the Italian definition as it comes from the European Directive regulation (section 4.4.1. NZEB, PEB, Low-e buildings: definitions).

Low energy building

There is no definition for Low energy building in the Spanish legislation, so it was decided to stick to the Italian definition as it comes from the European Directive regulation (section 4.4.1. NZEB, PEB, Low-e buildings: definitions).

4.3.2 METHODOLOGY

The calculations for LCA are done in One Click LCA software, following the EN15804+A1 standard (CEN, 2012). Generally, the methodology that has been followed is the same for the retrofitting scenario and for the new building construction, with some specificities for each of them, as it is shown below in **Table 27**.

Table 27. *Methodological aspects considered for the LCA.*

Methodological consideration	Renovated building	New building
The assessment considers a **50-year life span.**	✓	✓
The **results are normalized for the gross heated area** of the buildings chosen as case studies in square meters.	✓	✓
The possible benefits achievable through the exportation of renewable energy were individually documented in **module D**	✓ (only in the global cost)	x
The **energy generation and consumption** has been **accounted annually**	✓	✓
The **functional unit** for all measures is **square meters**	✓	✓
A **burden-free approach** has been considered for the retrofitting scenario. This approach does not take into consideration any maintenance or waste generated at the end of the life cycle for the materials inherited from the existing building.	✓	N/A

The boundaries of the analysis have been the same for each case-scenario. **Table 28** recalls the life cycle modules that are considered. The system boundaries include production stage (modules A1-A3), construction process (A4-A5), replacement and refurbishment (stage B4-B5), operational energy use (stage B6) and end-of-life stages: dismantling (C1) (only for new construction) and transport, waste processing and disposal (stages C2-C4) for both buildings. Benefits beyond the system boundaries (stage D) have been considered separately.

For the renovation scenario, in order to model the environmental impacts of stages A1 to A3, private datasets for the retrofitting solutions have been created in One Click LCA based on the environmental profiles of the complete solutions obtained from CYPE database (validated by BREEAM Spain (CYPE Ingenieros, 2018)). While for the new construction, One Click LCA database has been the main source of the information.

Table 28. *Life cycle modules considered.*

LCA module	Description	Included
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	✓
B1	Use	x
B2	Maintenance	x
B3	Repair	x
B4	Replacement	✓
B5	Refurbishment	✓
B6	Operational energy use	✓
B7	Operational water use	x
C1	Demolition, de-construction	✓ (only for new construction)
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	✓
	Renewable energy production	x
	Biogenic carbon	x

To model the module A4 the following assumptions were considered for the renovation case:

- The transportation distance has been always considered from the production site of the predominant materials. Thus, in cases where a complete solution was compounded by different types of materials and delivered from a unified storehouse such as, for example, ETICS (External Thermal Insulation Composite Systems), the distance considered has been the distance of the EPS panel, since it is the predominant material for the whole solution.
- Truck transportation until Valencia or Barcelona Port plus ship to Palma (Mallorca) has been considered for goods produced in Europe.
- For materials with production site in China, typically for electronical goods, the transportation considered has been a plane to Madrid and a plane from Madrid to Palma.

To model module B4 the following service lives were considered for the renovation case: 50 years for the insulation materials, 35 years for the windows, 20 years for heat pumps, 25 years for PV installations and 10 years for the inverters.

For the new construction, modules A4 and B4 have been calculated with the information obtained from the bill of materials provided by the architects or information derived from One Click for the specific cases.

Module B6 accounts for the impacts linked to the operational energy use and derived from preliminary energy simulations performed using TRNSYS (for renovation scenario) and CE3X tool (Efinovatic, 2023), (for new constructions).

It is worth noting that different emission factors were used for electricity in each of the buildings. For example, in the case of the renovation, the following emission factors were used based on the emission factors specific for the Balearic Islands (Government of Spain, 2016): electricity – 0.932 $kgCO_2/kWh$, natural gas – 0.252 $kgCO_2/kWh$ and butane – 0.254 $kgCO_2/kWh$. However, in the case of the new building, a factor proposed for Spain in the One Click LCA was used instead - 0.37 $kgCO_2/kWh$, similar to the factor found in ecoinvent – 0.323 $kgCO_2/kWh$.

Such a significant difference in coefficients can be explained by the fact that One Click LCA and ecoinvent propose factors for the whole Spanish territory. The main reason for the difference in the carbon footprint between Spanish mainland electricity generation and the generation in Balearic Islands is the energetic mix used for electricity generation, but also the difference in the kind of technologies used in both territories. Therefore, two different emission factors have been tested separately as preliminary assumptions: specific for the Balearic Islands (renovation scenario) and generic for the Spanish mainland (new construction) and will be harmonised in the future version of the document.

For the renovation case, market scenarios for the end-of-life stages for the retrofitting solutions/active systems have been defined based on the standard practice on the market and proposed by One Click based on the type of the material added to the private database/EPDs for the active systems. For the new construction, in some cases some specific scenarios for the end-of-life have been considered based on the information obtained from the architectural team. Benefits of recycling and reuse of the materials have been considered in stage D.

4.3.3. THE RENOVATION CASE STUDY

Several packages of active and passive retrofitting measures have been tested for the selected building in the design deliverable of the ARV project (more information can be found in the latest version of the ARV deliverable D4.3 “Design guidelines for zero-emission & positive energy refurbished and new buildings in Palma” (2023)).

To check different design alternatives against the building´s ambition levels described in Chapter 4.3.1, the following retrofitting scenarios have been considered (**Figure 13**):

- **Existing building (status quo).**
- **Low energy building (LEB) scenario (not feasible for the renovation goals of Palma demo)**: achieved by adding insulation to the walls, roof and first floor slab and implementation of the heat pump for DHW.
- **Nearly Zero Energy Building (NZEB) scenario:** achieved by adding insulation to the walls, roof and first floor slab, windows replacement, and implementation of the heat pump for DHW, PV system and a multisplit AC systems for heating and cooling.
- **Positive Energy Building (PEB) scenario:** not achievable for the renovation case due to the current condition of the building and limited space for the PV installation.

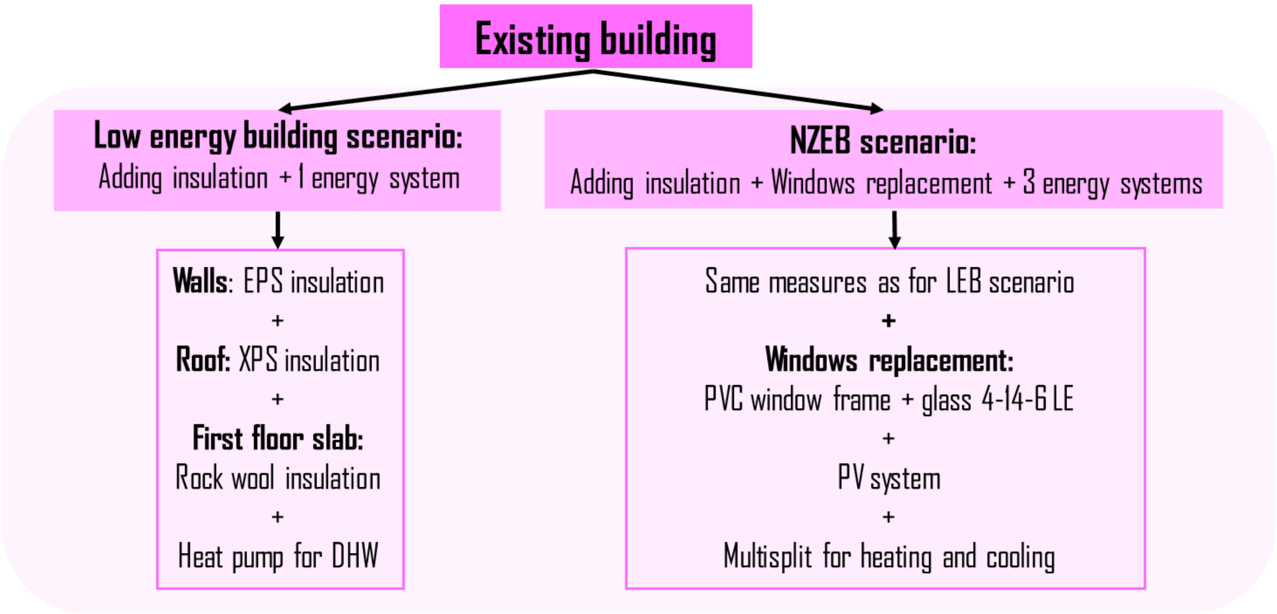


Figure 13. *Description of the retrofitting scenarios to achieve the low energy and NZEB building targets.*

As LEB scenario is not in line with the goals of the Palma demo and PEB scenario is not achievable for the considered building, environmental and economical performance of the NZEB scenario has been calculated and compared with the current situation of the building. Accordance of the selected NZEB scenario with the requirements from the Spanish legislation described in chapter 4.3.1 is presented in **Table 29**.

Table 29. *Accordance with NZEB requirements defined by Spanish code CTE (renovated building).*

Technical requirement	Units	Limiting values for renovated buildings	Renovation case	Verification
Non-renewable primary energy consumption (H0)	kWh/m^{2}y	68.75	26.21	✓
Total primary energy consumption (H0)	kWh/m^{2}y	92	26.93	✓
Features of the thermal envelope (H1)	W/m^{2}K	Walls and floors facing outdoor space: 0.56	0.471 (walls) 0.524 (first floor slab)	✓

		Roofs in contact with outdoor space: 0.44	0.380	✓
		Walls, floors, and roofs in contact with non-residential spaces or the ground: 0.75	N/A	N/A
		Windows and blind spaces: 2.3	1.3 (PVC frame) 1.69 (glass)	✓
		Doors with more than 50% transparent surface: 5.7	N/A	N/A
Renewable energy generation for DHW (H4)	Percentage of renewable energy powering DHW	70% of renewable consumption for buildings consuming more than 5 000 litres per day	The consumption of the building is higher than 5 000 litres per day, so at least 70% of renewable energy powering DHW is expected	✓
	Seasonal Coefficient of performance	At least SCOP of 2.5 when the heat pump is powered with electricity	3.17	✓
Renewable energy power installed (H5)	Power installed (kW)	P1 = $F_{pr;el}$ * S = 21.8 kW	49.5	✓
		P2= 0.1 * (0.5*S_c – S_{oc}) = 8.5 kW		
Minimum of charging infrastructure for electric vehicles (H6)	Number of parking lots with the needed infrastructure installed to connect a charging station	100% of the parking lots	N/A	N/A

Results

Figure 14 and **Figure 15** present an overview of the contribution to GWP (Global Warming Potential) of each of the LCA phases for the renovation of selected building with a NZEB ambition level.

In **Figure 15** stages accounting for less than 1% of GWP have not been illustrated.

The embodied impacts (modules A1-A3) account for 10% of the total GWP – 1.58 $kgCO_2/m^2y$ (**Figure 15**). Even though the closest source of materials was considered for the preliminary calculations, the A4 stage is not negligible and contributes to 2% as most of the materials must be transported from outside the island.

The B4-B5 stage contributes a significant 16% of total GWP as most of the materials such as windows and energy systems need at least one replacement along the life cycle of the renovated building. The operational energy use (B6 stage) is contributing the most to GWP with a significant 61%, accounting for 8.29 $kgCO_2/m^2y$.

This significant contribution of operational energy in total GWP can be explained by the source of energy used for electricity generation in the Balearic Islands, which uses a significant number of non-renewable sources.

Finally, waste processing contributes to 10% of all the GWP. However, different end-of-life scenarios such as incineration or recycling contribute to benefits accounted for in stage D.

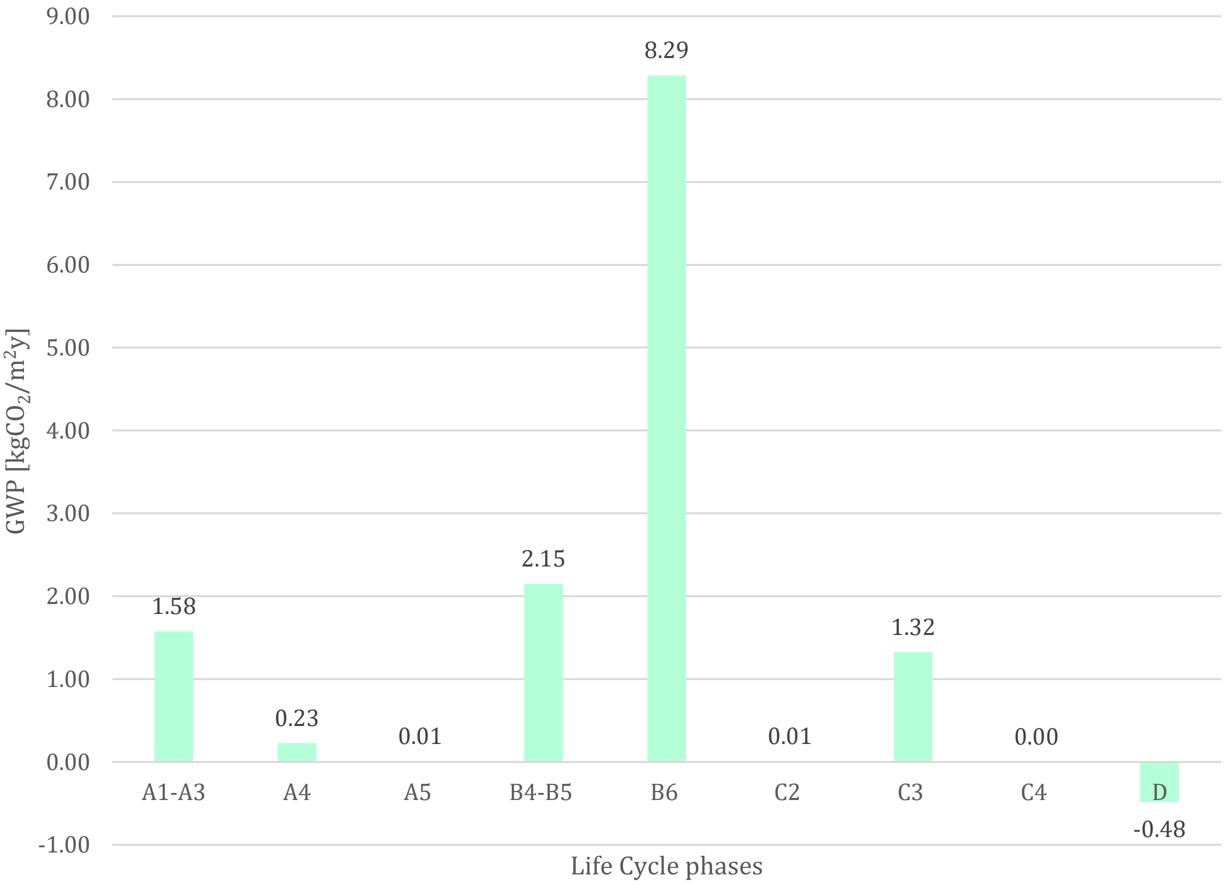


Figure 14*. Global warming potential contribution for each Life Cycle phase in $kgCO_2/m^2y$ (renovation scenario).*

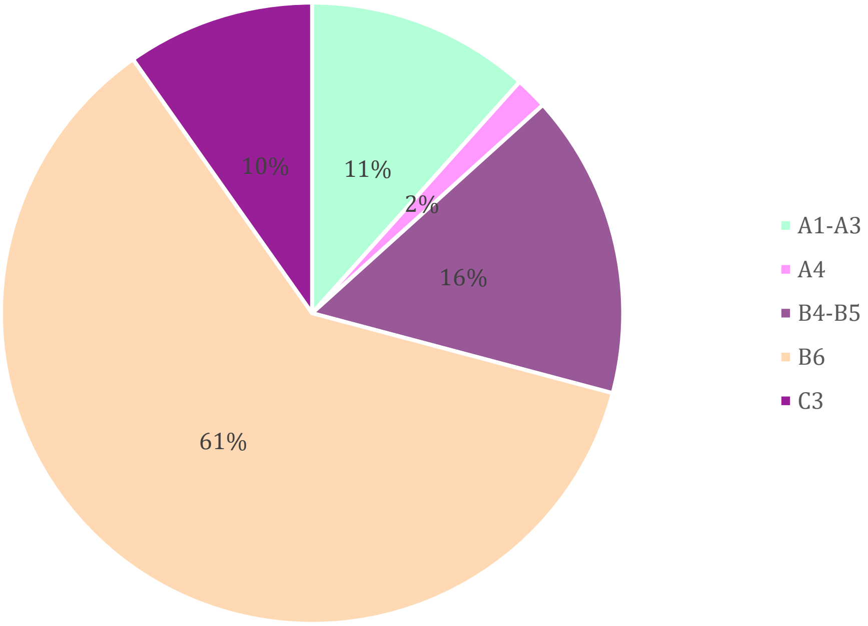


Figure 15. Share of the different life cycle phases in the total (module D excluded) (renovation scenario).

In addition, **Figure 16** represents the flow that goes from the life-cycle stage to the classifications into the resource types. As has been explained above the high amount of GWP associated with B6 stage (operational energy) is due to the source of energy used to produce electricity in the Balearic Islands. B4 and B5 stages associated with building parts and energy systems replacement are mostly contributed by the replacement of active measures such as HVAC equipment, where windows replacement has a significantly smaller contribution to these stages. The waste processing GWP is mostly associated with the waste generated by the XPS insulation on the roof. The embodied impacts are produced predominantly with the production of energy systems, in contrary, insulation materials have a smaller contribution to this stage.

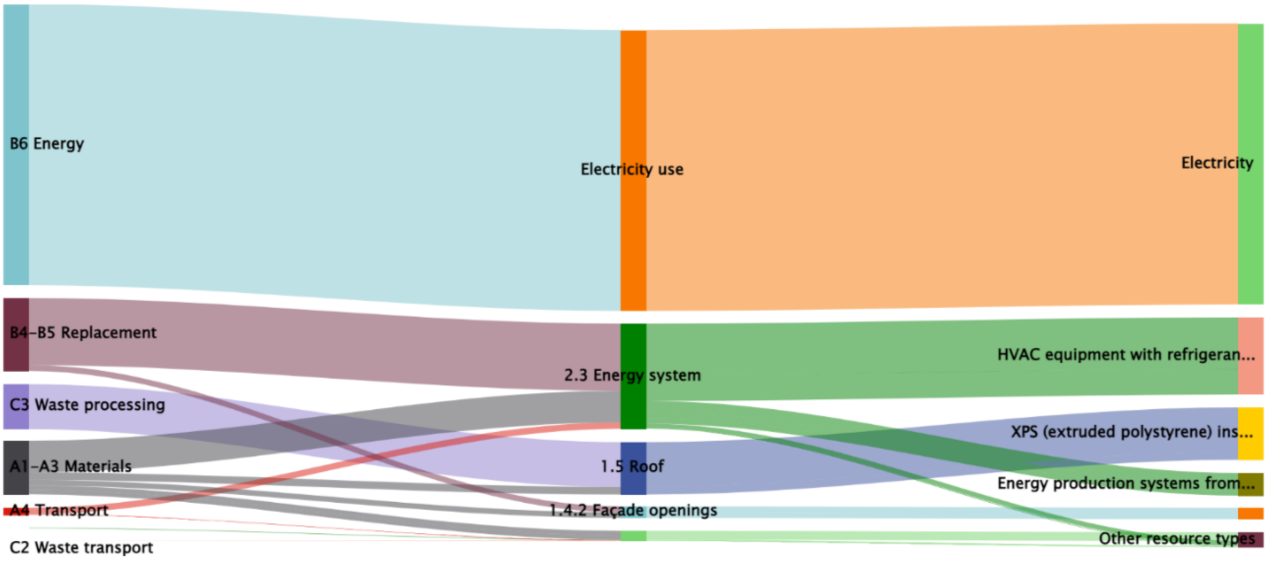


Figure 16. Sankey diagram for the GWP of the renovation case. Image from One Click.

As the preliminary estimation of the economic performance, the global costs of the renovation case have been calculated for 50 years of the life cycle of the building. To calculate the global costs, electricity inflation, facilities deterioration, maintenance costs, replacement costs, the cost of investment (including subsidies) and the cost of energy for each of the technologies have been considered. Economical concepts detailed in Chapter 4.3.2 of ARV deliverable 4.3 mentioned above. The cost of energy considers the market selling price of the surplus produced by the photovoltaic solar field.

Figure 17 shows a comparison of the global costs in euros per dwelling for the base case and the retrofitting scenario. The increased investment in replacements is partly compensated by the grants available for energy retrofitting. The maintenance cost is similar in both scenarios. Instead, the savings related to energy consumption are very significant, representing a 95% reduction of the costs of energy consumption over 50 years after retrofitting.

Scenarios assessment

Table 30 presents the comparison of GWP between the base case considering just stage B6 – operational energy and the retrofitting scenario considering all stages described in the previous chapter. Based on the results, a 74% reduction of annual GWP would be achieved compared to the base case considering a 50-year life cycle.

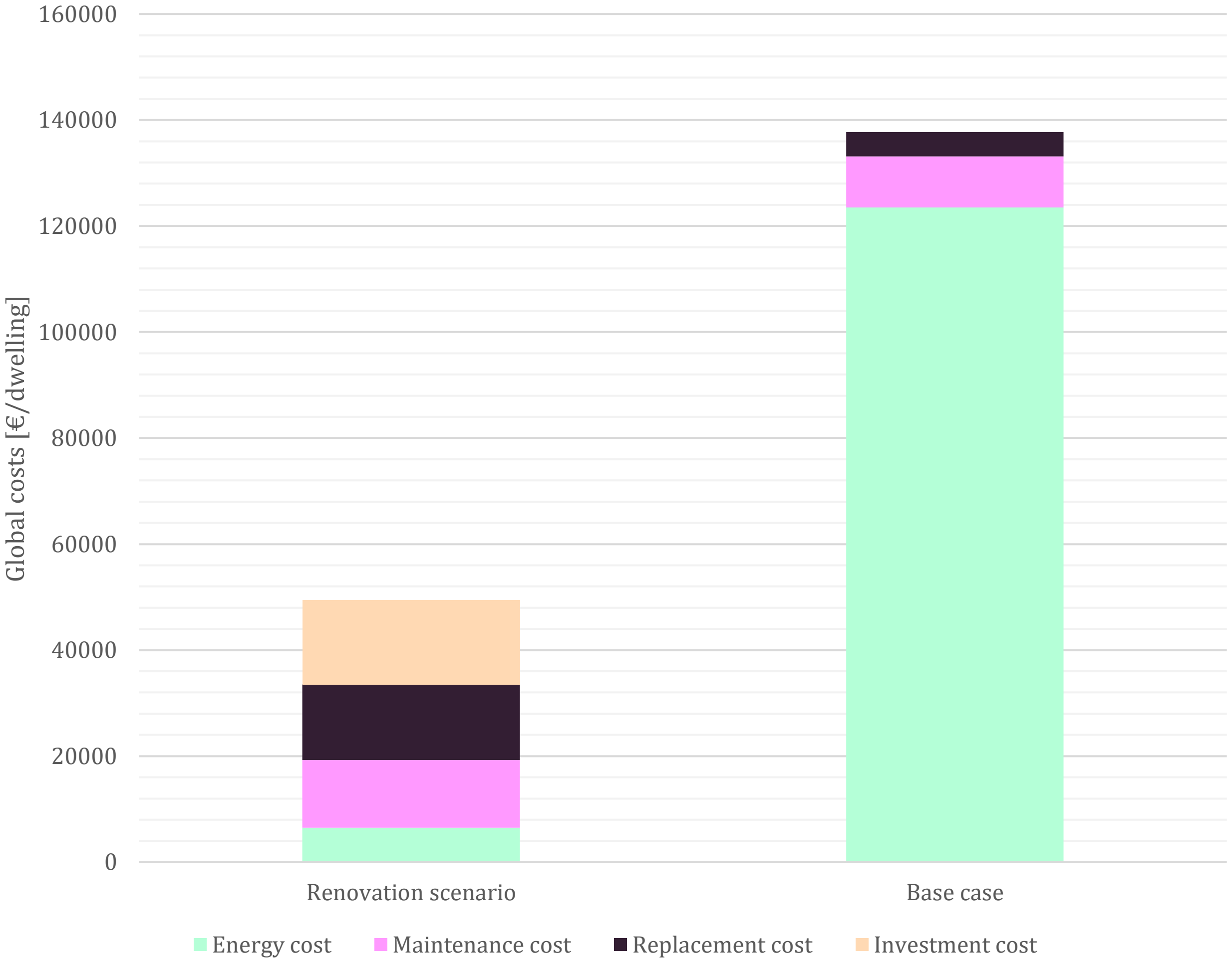


Figure 17. *Global costs of the renovation scenario over 50-year time span.*

***Table* 30.** *Comparison between the GWP of the base case and the renovation scenario.*

	Base case	**Renovation scenario**
GWP [$\text{kgCO}_2/\text{m}^2\text{y}$]	52.72	13.58
Life cycle phases	Only use stage B6	Production stage (modules A1-A3), construction process (A4-A5), replacement and refurbishment (stage B4-B5), operational energy use (stage B6) and end-of-life stages: transport, waste processing and disposal (stages C2-C4)

Based on the results obtained in **Figure 17**, implementation of the passive and active energy efficiency measures in the considered renovation scenario will lead to 64% reduction in the global costs in 50 years compared to the current stage of the building, while giving a significant reduction in the energy costs.

Therefore, it can be concluded that the retrofitting scenario considered will positively impact both on the environmental and the economic performance of the renovated building.

4.3.4. NEW SOCIAL HOUSING BUILDING

Fornaris is a 35-unit residential building in Palma. A low-tech design based on load-bearing walls is proposed, which helps to drastically reduce the environmental impact of the construction and improve the thermal inertia of the dwellings, while establishing a tectonic dialogue with the surrounding buildings. All the apartments have natural cross-ventilation, which together with the captivating use of the double thermal intermediate spaces acting as greenhouses (front and back), solar control and thermal inertia, allows a very low energy demand while maintaining a high level of comfort.

This building was initially designed to achieve an annual net zero energy demand. In the original project 52 PV panels were covering the 73.8% (23 241 kWh/y) of the energy demand (31 479 kWh/y). In August 2023, the project was revised to become a Positive Energy Building (PEB), so that the energy generated by the PV system will be, at least, equal to energy demand considering heating, cooling and DHW. The revised project considers the installation of a Building-Applied Photovoltaics (BAPV) system, consisting of 88 PV panels on the roof connected to the grid.

Therefore, in order to compare different design alternatives against the building´s ambition levels described in Chapter 4.3.1, the following scenarios have been considered:

- **NZEB,** which is the legal minimum standard for new buildings in Europe**:** the initial project proposal for the PV installation with 52 panels.
- **LEB,** which represents a design scenario with an ambition level that is below the legal minimum: the building without PV installation.
- **PEB,** which exceeds the legal minimum standard but is a requirement for the ARV project: current proposal with 88 panels.

Although the increase in the number of solar panels means an increase in carbon emissions during the construction of the building (phases A1-A3) of approximately 5 189.94 kgCO_2 (96.11 kgCO_2/m^2 of PV panel), these emissions are offset by the energy production during the lifespan of the building. If the GWP of the electricity generated conventionally in the Balearic Islands (0.932 kgCO_2/kWh) with the energy generated by PV panels (0.0683 kgCO_2/kWh), there is a reduction of –93%. After 6 months, the increase in emissions during the construction phase may be offset by the emissions saved during energy generation.

Table 31. *Accordance with NZEB requirements defined by Spanish code CTE (new building).*

Technical requirement	Units	Limiting values for new buildings	New construction scenario	Verification
Non-renewable primary energy consumption (H0)	kWh/m²y	35	0	✓
Total primary energy consumption (H0)	kWh/m²y	64.4	34.7	✓
Features of the thermal envelope (H1)	W/m²K	Walls and floors facing outdoor space: 0.56	0.29-0.36	✓
		Roofs in contact with outdoor space: 0.44	0.17	✓
		Walls, floors, and roofs in contact with non-residential spaces or the ground: 0.75	0.26	✓
		Windows and blind spaces: 2.3	1.28	✓
		Doors with more than 50% transparent surface: 5.7	1.28	✓
Renewable energy generation for DHW (H4)	Percentage of renewable energy powering DHW	60% of renewable consumption for buildings consuming more than 5.000 litres per day	Building consuming 2 016 litres per day (less than 5.000 litres per day). 100% of renewable consumption > 60% required	✓

	Seasonal Coefficient of performance	At least SCOP of 2.5 when the heat pump is powered with electricity	2.94	✓
Renewable energy power installed (H5)	Power installed (kW)	$P1 = F_{pr;el} * S = 16.5$ kW $P2 = 0.1 * (0.5 * S_c – S_{oc}) = 34.9$ kW	31.68	✓
Minimum of charging infrastructure for electric vehicles (H6)	Number of parking lots with the needed infrastructure installed to connect a charging station	100% of the parking lots	Pre-installation of 100% of the parking lots	✓

As LEB and NZEB scenarios are not in line with the goals of the project, only environmental performance of the PEB scenario has been presented. Global cost of the building was not calculated at the current stage of the project due to the lack of data and will be calculated as the project evolves.

Accordance of the selected PEB scenario with the minimum requirements according to the Spanish legislation described in chapter 4.3.1 is presented in **Table 31**.

Accordance with PEB requirements defined in chapter 4.3.1 is presented in **Table 32**.

Table 32. *Accordance with PEB requirements.*

Technical requirement	New construction case
Significantly more than 50% of the global energy requirement of the building (namely for heating, cooling and DHW) is balanced by renewable energy resources	100% of the global energy (heating, cooling and DHW) is balanced by renewable energy resources
Significantly more than 50% of the energy requirement of the building for DHW is balanced by renewable energy resources	100% of energy for DHW is balanced by renewable energy resources
Minimum electrical power of the renewable energy systems integrated in the building or nearby equal to 1/50 of the building footprint	804.21 m^2/50= 16.08 kW < 31.68 kW peak PV system

Results

The LCA developed for the new social housing building has followed the methodology described in chapter 4.3.2. It´s worth to mention that on the current stage of the project only preliminary results are presented and will be revised throughout the lifetime of the project.

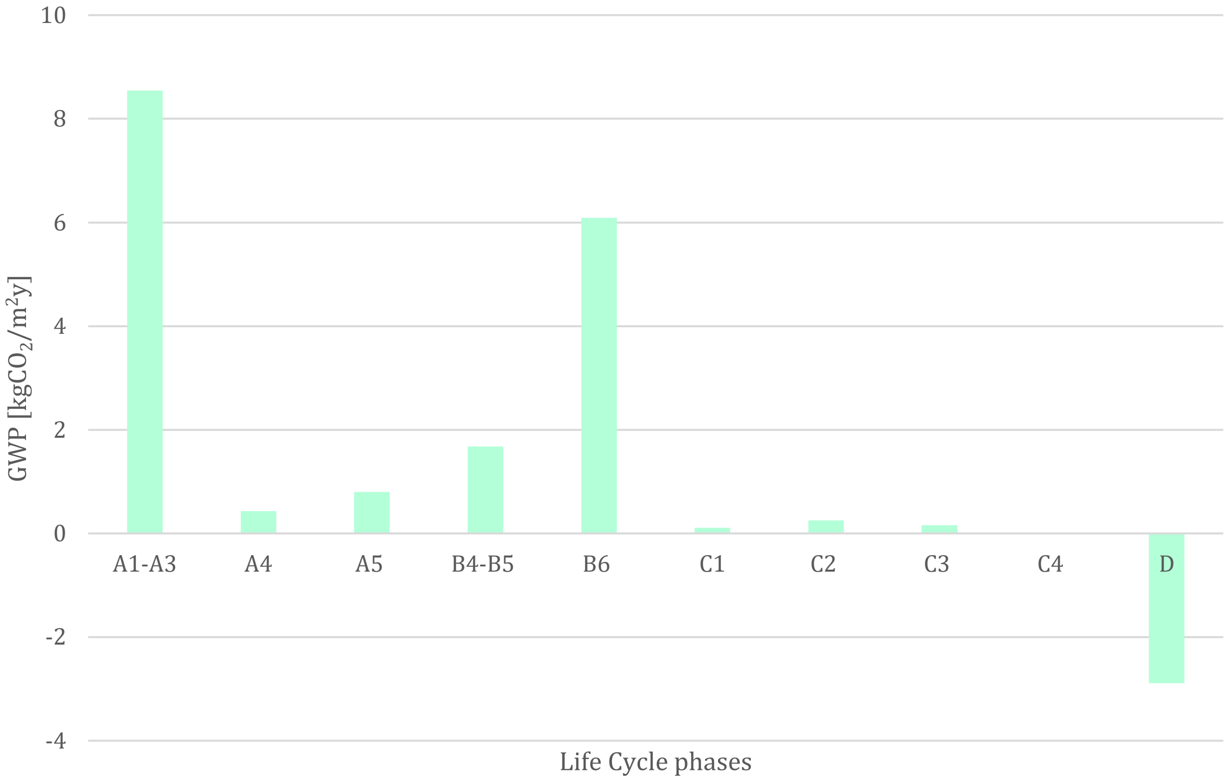


***Figure 18.** Global warming potential contribution for each Life Cycle phase in kgCO$_2$/m^{2}y (new construction case).*

Figure 18 and **Figure 19** present an overview of the contribution to GWP of each of the LCA phases for the new construction with a PEB ambition level. In **Figure 19** stages accounting for less than 1% of GWP have not been illustrated.

As expected, most of the CO$_2$ emissions (47%) are produced during the extraction, transport, and manufacturing of the materials (A1-A3 stages), accounting for 427 kgCO$_2$/m^2. This value is in line with the initially set targets of a -25% carbon emissions reduction in these stages compared with a reference value of 750 kgCO$_2$/m^2, achieving a -43% reduction. Stages A4 and A5 contribute to 2% and 5% of total GWP respectively. Relatively low share of the transport emissions can be explained by the preference of the local materials for the new construction.

Regarding the use stage, the operational energy use (B6 stage) is contributing to GWP with a significant 34%, accounting for 304 kgCO$_2$/m^{2}y. The B4-B5 stage contributes to 9% of GWP, as even though most of the buildings materials or technologies have a service life as building, some of them still need at least one replacement along the life cycle of the building.

The end-of-life stages (C1-C4) in total contribute to the less than 3% of total GWP. In contrast, benefits beyond system boundaries such as materials reuse or recycling would positively contribute to GWP reduction and potentially can reduce the total GWP on 16% or 2.9 kgCO$_2$/m^{2}y.

As a summary, **Figure 20** represents the flow that goes from the life-cycle stage to the classifications into the resource types.

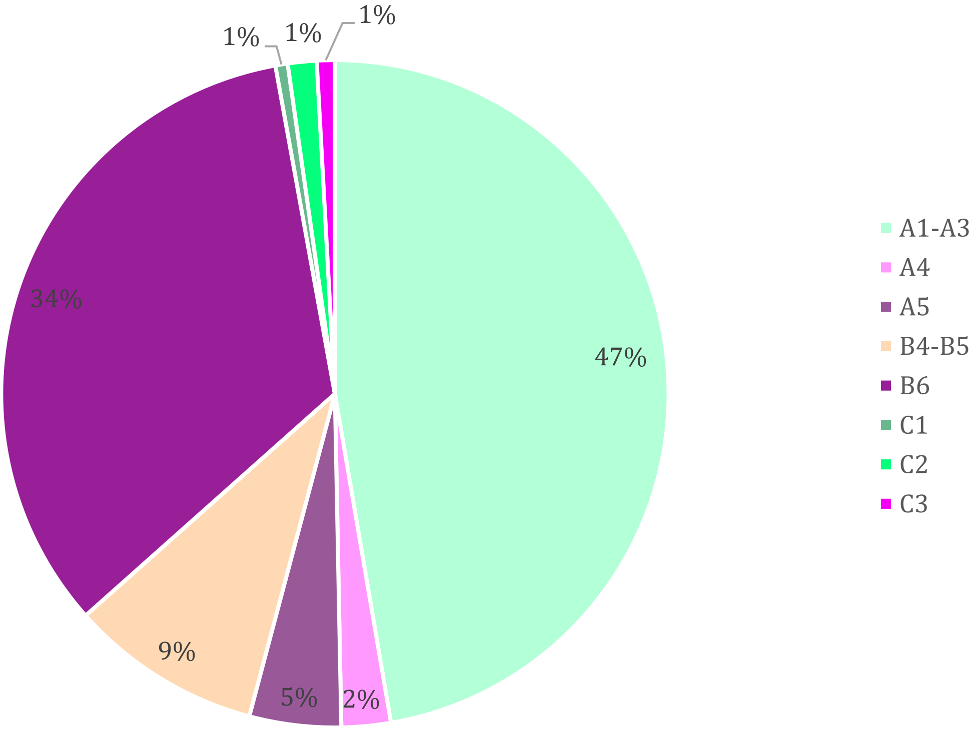


Figure 19. Share of the different life cycle phases in the total (module D excluded) for new construction scenario.

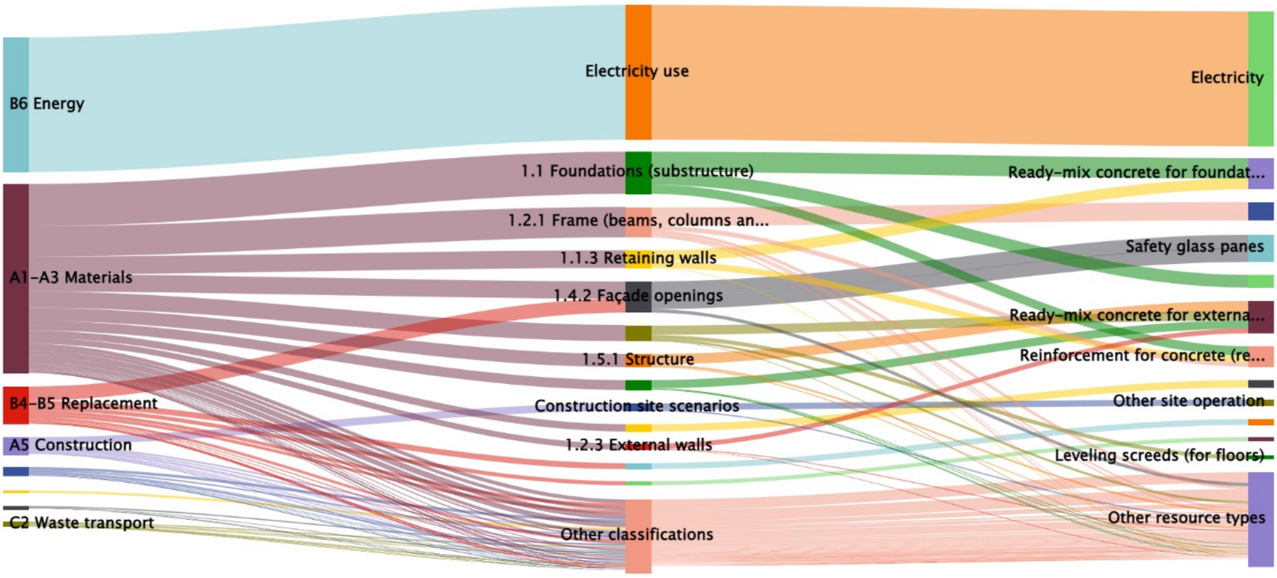


Figure 20. Sankey diagram for the GWP of the new building. Image from One Click.

As explained above, due to the lack of the data at the current stage of the project, it was not possible to calculate the global cost of the new construction. The initial investment cost of the prototype is around 6.5 million euros, while estimation of the energy, maintenance and replacements costs is planned to be completed in the upcoming months.

4.4. TRENTO DEMO

4.4.1. NZEB, PEB, LOW-E BUILDINGS: DEFINITIONS

Nearly zero energy building

In Italy, the features of NZEBs were established by the Ministry Decree dated 26 June 2015, known as the "Minimum requirements". This decree served as a technical foundation for the legislation that implemented European directives related to the energy performance of the building sector (e.g., EPBD 2010/31/EU). NZEB should fulfil both the performance standards established by the “Minimum requirements” decree and the obligations for the integration of renewable sources as mandated by Legislative Decree 28/2011, denominated “Decree renewables”.
In particular, the following performance requirements should be respected:

- All the requirements provided by letter b), paragraph 2, sub-paragraph 3.3 of the “Minimum requirements” decree, which guarantee a very high energy performance of the building.
- The obligations of integration of renewable sources in compliance with the minimum levels set out in Annex 3, paragraph 1, letter c) of the “Decree renewables”, which guarantee a significant coverage of the energy requirement of the building through the utilization of renewable energy sources.

***Table 33**. NZEB requirements in Italy (source: ENEA).*

Minimum requirements in NZEB design (DM 26.06.2015)		
H'_T [W/m^{2}K]	Average coefficient	$H'_T < H'_{T,\ limit}$ that depends on the climatic zone and the S/V ratio
$A_{sol,est}$ / $A_{sup\ utile}$	Equivalent solar area in summer per unit of useful surface.	$A_{sol,est}$ / $A_{sup\ utile}$ < threshold limit depending on the category of the building
η H	Average seasonal efficiency of the heating (H), cooling (C) and DHW (W) systems.	$\eta_H < \eta_{H,limit}$
η C		$\eta_C < \eta_{C,limit}$
η W		$\eta_W < \eta_{W,limit}$
$EP_{H,nd}$ [W/m^{2}K]	Heating energy performance index	$EP_{H,\ nd} < EP_{H,\ nd,\ limit}$ related to the refence building
$EP_{C,nd}$ [W/m^{2}K]	Cooling energy performance index	$EP_{C,\ nd} < EP_{C,\ nd,\ limit}$ related to the refence building
$EP_{gl,nd}$ [W/m^{2}K]	Global energy performance index (including heating, cooling and DWH)	$EP_{gl,\ nd} < EP_{gl,\ nd,\ limit}$ related to the refence building
U [W/m^{2}K]	Average thermal transmittance of the envelope (walls, roofs, floors, windows, …)	$U<U_{ref}$ related to the refence building
Integration of renewable energy sources (D. Lgs. 28.2011)		
Minimum percentage of consumptions for heating, cooling and DHW covered by renewable sources equal to **50%.**	Minimum percentage of consumptions for DHW covered by renewable sources equal to **50%.**	Minimum electrical power of the renewable energy systems integrated in the building or nearby equal to **1/50 of the building footprint**.

Table 33 resumes all the requirements that should be accomplished to realize a NZEB in Italy.

An essential characteristic of the NZEBs is their capability to exchange energy with one or more distribution grids, such as electricity or district heating ones. The **physical boundaries** for the installation of renewable energy systems are related to a specific Point of Delivery (POD) for the electricity balancing: the energy analysis examines energy flows at the connection point to supply grids, encompassing power, heating, or the fuel delivery chain. From this perspective, "on-site generation" systems are within the building distribution grid and before the grid meter; off-site systems are not accounted. The focus of the balancing is therefore a single consumption client, whether we are talking about single-family or multi-family buildings.

As it can be noted, the **energy uses** that are considered in the balancing are the ones related to the heating, cooling, and domestic hot water (thus consumptions for ventilation, lighting, domestic appliances or electric vehicles are excluded). Lighting is included in the case of non-residential buildings. Energy uses that are not linked to the operational phase are not counted: embodied energy/carbon of building materials, for instance, is not accounted in the calculation of the NZEB balance.

The balance, usually based on the calculation of the primary energy required and generated by the building (kWh/m^{2}y o kWh), is calculated on an annual basis. The primary energy **conversion factors** are defined by legislation and a symmetrical weighting is used for imported and exported flows (or load-generation ones). In this way the energy flows delivered by the grid and fed into the grid have the same value.

Two **typologies of balancing** are allowed:

- **Imported/exported balance (or weighted demand/weighted supply)**
- **Load/generation balance**

The main difference between the two balancing typologies is that, in the first case, a detailed estimation of the «self-consumption» of the building should be available even during the design stage. In order to have enough knowledge about the renewable generation that is immediately absorbed by the building, detailed data about the building loads should be available with an adequate time resolution. Since most of the times these requirements are not met and energy simulations are performed on a monthly basis (using semi-stationary codes), load/generation balance is usually preferred. A monthly resolution simulation is, in fact, not able to properly investigate grid-building interactions, while high-resolution simulations or monitoring are necessary to describe self-consumption patterns and detect temporal matching profiles. The methodology that is generally applied by the simulation codes is the so called net monthly balance:

$$\sum g_{m,i}\, w_{g,i} - \sum l_{m,i}\, w_{l,i} = G_m - L_m \geq 0$$

$$g_{m,i} = \sum max[0, g_i(m) - l_i(m)]$$

$$l_{m,i} = \sum max[0, l_i(m) - g_i(m)]$$

Where

$g_i(m)$ is the monthly energy generation for the energy vector i;
$l_i(m)$ is the monthly energy load for the energy vector i;
$w_{g,i}$ is the primary energy conversion factor for the generated energy vector i;
$w_{l,i}$ is the primary energy conversion factor for the load i.

This simplified approach, generally overestimates the load/generation matching, whereas higher exports are usually obtained when adopting a more detailed time resolution in simulations.

Starting from the definition of NZEB, which is the only one defined by legislation in Italy, it is possible to derive the definition of low-energy building or plus energy building.

Plus energy building

A Plus or Positive Energy Building (PEB) is a building that generates more energy than it consumes over the course of a year. This general concept has not a translation into the Italian legislation. Since PEBs cab be conceived as an evolution of NZEBs, they can be defined as NZEBs in which the obligations of integration of renewable sources established by the "Decree renewables" are met with a significant confidence level. This means, that:

- significantly more than 50% of the global energy requirement of the building (namely for heating, cooling and DHW) is balanced by renewable energy resources.
- significantly more than 50% of the energy requirement of the building for DHW is balanced by renewable energy resources.
- the minimum electrical power of the local renewable energy systems is significantly higher than the 1/50 of the building footprint.

Low energy building

A low-energy building is commonly conceived as a building with a lower operational energy consumption in comparison with the common practice. The installation of insulation materials is indeed one of the primary strategies applied to reduce the energy consumption of buildings. The insulation helps to improve the thermal efficiency of a building by reducing heat transfer through walls, roofs, and floors. This means that less energy is needed for heating in cold climates and for cooling in warm climates, ultimately leading to a lower energy consumption and reduced utility costs.

In addition to the insulation, other strategies to improve energy efficiency in buildings include:

- the installation of high energy performance windows and doors with proper seals and glazing to minimize air leakage and heat transfer.
- the upgrading of heating, ventilation, and air conditioning (HVAC) systems to more efficient models.
- the replacement of the traditional incandescent and fluorescent lamps with energy-efficient LED lighting.
- the installation of solar panels or wind turbines to generate renewable energy on-site.
- the implementation of smart building technologies and automation systems to optimize energy usage by adjusting heating, cooling, and lighting based on occupancy and external conditions.
- the incorporation of passive design principles, such as orienting buildings to maximize natural lighting and ventilation, to reduce the reliance on artificial lighting and HVAC systems.
- the usage of energy-efficient appliances and equipment.
- the implementation of water-saving measures and practices to indirectly lower energy consumption by reducing the energy required for water heating.

By combining these strategies and adopting a holistic approach to building design and operation, it is possible to achieve significant reductions of the energy consumption in the built environment (Asdrubali and Desideri, 2019).

Considering the current Italian legislation about the energy efficiency in the building sector, it is expected that a low-energy building, characterized by high energy performance, complies with all the requirements outlined in the "Minimum requirements" decree. However, it may not fully or partially meet the renewable energy balancing requirements specified in the "Decree renewables."

4.4.2. METHODOLOGY

The methodology is structured following the most updated standards on buildings LCA, that are already cited in the previous sections (e.g., EN 15978, EN 15804). The scope of the analysis is to compare different design ambition levels, namely NZEB, PEB or low-energy buildings.
The assessment considers a 50 years life span and the results are normalized for the gross heated area of the buildings chosen as case studies.
A cut-off approach is adopted, which means that the potential benefits of recycling materials were not modelled through the entire recycling process. The possible benefits achievable through the recycling

and reuse of materials as well as those associated with the exportation of renewable energy and biogenic carbon, were individually documented in module D. This approach also means that for renovations, the materials inherited from the existing building are treated as having no environmental burdens. The modelling does not account for any maintenance of these materials or waste produced at the end of their life cycle, but it considers the waste generated during renovation works.

Table 34 recalls the life cycle modules that are considered. The system boundaries include the construction phase (modules A1-A4), replacements of building components (module B4), operational energy use (module B6) and end-of-life (modules C1-C4).
Considering the module A4, if transportation wasn't originally integrated into the process used in the modelling, we assumed a transportation distance of 60 km to the construction site.

Table 34. *Life cycle modules considered.*

LCA module	**Description**	**Included**
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	x
B1	Use	x
B2	Maintenance	x
B3	Repair	x
B4	Replacement	✓
B5	Refurbishment	x
B6	Operational energy use	✓
B7	Operational water use	x
C1	Demolition, de-construction	✓
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	x
	Renewable energy production	✓
	Biogenic carbon	✓

In order to model the module B4 the following service lives were considered (see **Table 35**): 35 years for windows, 25 years for wall linings, 10 years for wall coverings, 20 years for services, 25 years for PV power plants and 10 years for batteries.

Module B6 accounts for the impacts linked to the operational energy use for heating and DHW. The data are derived from the preliminary energy simulations performed using a static energy modelling tool. The scope of these simulations was to realize an energy audit of the building, to fill in the energy certificate or to compile the report required by the Italian legislation for energy renovations (law n.10 of 1991).

The substitution principle is applied to evaluate the benefits achievable in the module D.
ecoinvent v3.9 was used as the main background database for LCA modelling while local price lists were adopted for cost calculations.
Results are aggregated in:

- Embodied impacts (modules A1-A4)
- Embodied recurring impacts (module B4)
- Operational impacts (module B6)
- End-of-life impacts (modules C1-C4)
- Benefits achievable (module D)

Table 35. *Values of the service life of building components considered in the assessment.*

Agreed service life of building components		
Structural systems	Concrete, steel	100 years
Structural systems	Wood	50 years
Insulation layers, coating	EPS, XPS, rock wool	50 years
Windows	Glass and frames	35 years
Energy systems	Boilers, heat pumps	25 years
Energy systems	PV systems	25 years
Energy systems	Batteries	10 years

4.4.3. THE RENOVATION CASE STUDY

The renovation consists of a multifamily residential building located in Povo (about 5 km from Trento, Northen Italy). The village is located at 398 m.a.s.l. and the location is classified in the climatic zone E with 2567 heating degree days; it should be underlined that the buildings located above 430 m.a.s.l. in the Province of Trento are classified in climatic zone F (heating degree days above 3000). The building is composed of nine apartments consisting of 561m^2 of heated surface.

The renovation mainly regards the upgrading of the building envelope with the installation of two typologies of insulation panels: a traditional coat realized in EPS and phenolic foam panels and a more innovative layout realized through a prefabricated panel called Renew-wall. Considering the envelope, the intervention also regards the insulation of the attic with a 16cm layer of XPS laid on the floor, and the substitution of some windows, based on residents' willingness.

From the energy systems side, the intervention is characterized by the installation of a photovoltaic power plant (19.68 kWp) integrated in the roof and equipped with a 40-kWh storage system consisting of two Li-Ion battery packs 20 kWh each. The system covers the electrical consumptions of the condominium. Furthermore, in two apartments the old gas boilers were replaced with a hybrid heat pump plus condensing boiler system, while the remaining apartments opted for a straightforward replacement with new condensing boilers.

Considering the Italian legislation, the renovation implemented basically results in a low energy intervention because not all the requirements for NZEB are met.

Table 36. *NZEB requirements achieved and not in the renovation in Povo.*

Minimum requirements in NZEB design (DM 26.06.2015)		
H'_T [W/m^{2}K]	Average coefficient	✓
$A_{sol,est} / A_{sup\ utile}$	Equivalent solar area in summer per unit of useful surface.	Not met
η H	Average seasonal efficiency of the heating (H), cooling (C) and DHW (W) systems.	Not met
η C		Not met
η W		Not met
$EP_{H,nd}$ [W/m^{2}K]	Heating energy performance index	Not met
$EP_{C,nd}$ [W/m^{2}K]	Cooling energy performance index	Not met
$EP_{gl,nd}$ [W/m^{2}K]	Global energy performance index (including heating, cooling and DWH)	Not met
U [W/m^{2}K]	Average thermal transmittance of the envelope (walls, roofs, floors, windows, …)	Not met
Integration of renewable energy sources (D. Lgs. 28.2011)		
Minimum percentage of consumptions for heating, cooling and DHW covered by renewable sources equal to **50%.**	Minimum percentage of consumptions for DHW covered by renewable sources equal to **50%.**	Minimum electrical power of the renewable energy systems integrated in the building or nearby equal to **1/50 of the building footprint**.
✓	Not met	✓

Table 36 recaps the requirements that are achieved and not achieved.

However, considering an annual balance between load and generation and the primary energy conversion factors in force in Italy, the renewable energy produced by the PV plant is able to cover the 50% of the primary energy requirement of the building for heating and DHW. Furthermore, the thermal resistance of the vertical wall is below the limits imposed by the Italian legislation for the reference NZEB building. However, as shown in the following section, considering ecoinvent primary energy conversion factors, the renovated building is characterized by a nearly zero energy balance.

To resume, basically, two retrofitting scenarios were considered:

- Ex ante or status quo, which considered the performance of the building before the renovation.
- An energy renovation which results in a low-energy building following the Italian legislation. However, considering ecoinvent characterization factors, the primary energy balance of the multifamily house after the renovation is positive and thus the building can be considered a NZEB.

4.4.4. RENOVATION: RESULTS

Figure 21 illustrates the components that represent a hotspot for both the embodied GWP and non-renewable CED of the renovation in Povo. More specifically, the intervention takes the form of a deep envelope insulation, wherein the insulation materials defining the coating play a crucial role in influencing the embodied impacts.

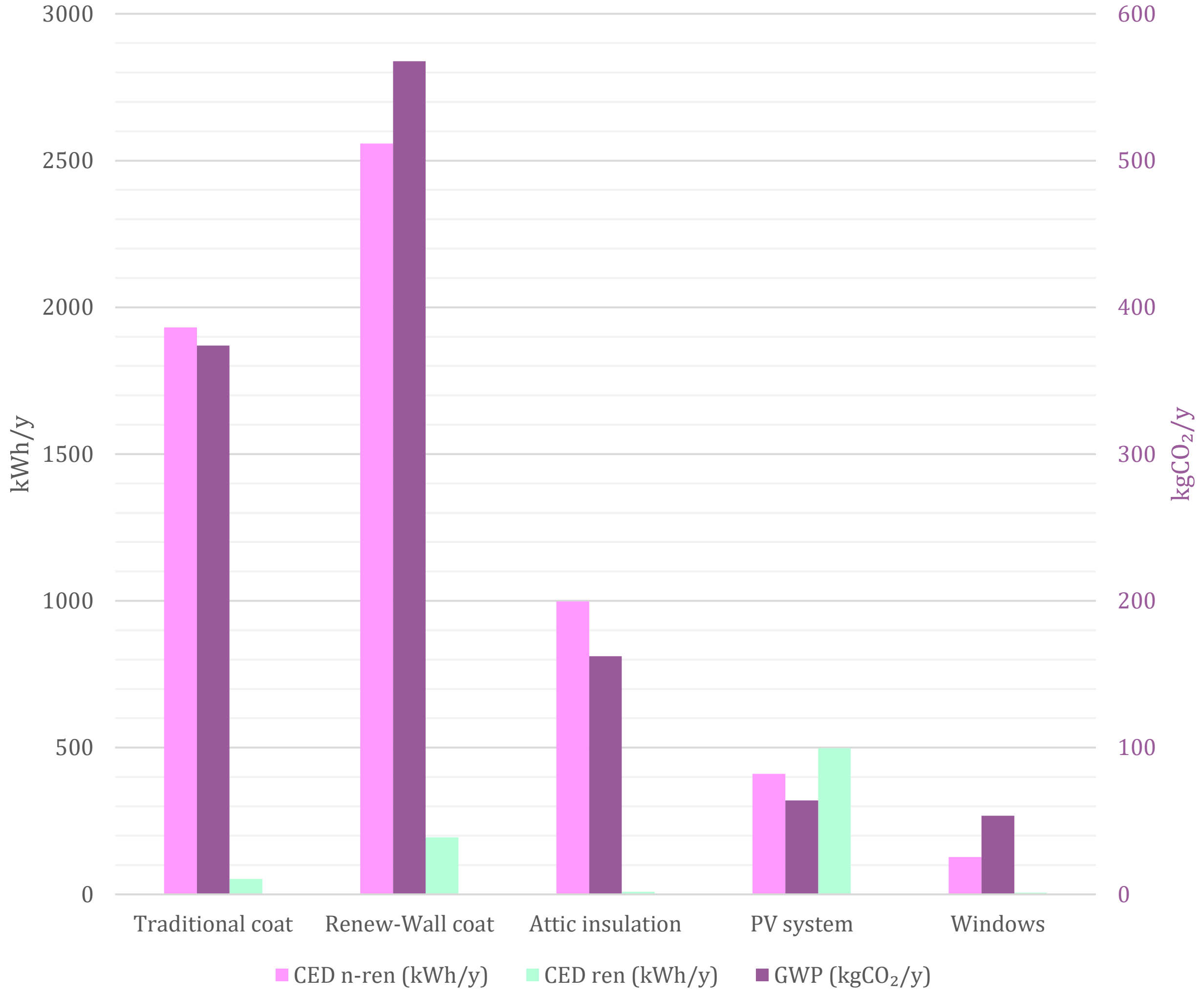


Figure 21. Contribution analysis for the renovation in Povo.

The primary energy requirement (kWh/m²y) and the carbon dioxide equivalent emissions (kg CO_2-eq/m²y) associated with different phases of the renovation life cycle are presented in **Figure 22** and **Figure 24** while their percentage contribution to the total is displayed in **Figure 23** and **Figure 25**.

The 'cradle to grave' non-renewable CED turned to be equal to 143 kWh/m²y, with only 8.8 kWh/m²y of additional renewable contribution. It suddenly emerged that most of the primary energy requirement, around 87% of the total, was linked to the building operational energy use (module B6). The embodied impacts (modules A1-A4) represented the 7% of the total while the primary energy requirement related to the end-of-life or to the transportations to the construction site (module A4) resulted quite negligible, with an incidence that of 1% (see **Figure 23**). On the other hand, the contribution of module B4 resulted significant (5%) because at least one substitution was considered for windows and for each energy system component that is added or upgraded in the renovation.

Looking at CED figures, it is interesting to notice that the electricity produced by the photovoltaic system is able to save about the 150% of the life cycle non-renewable CED of the renovation.

The results about the GWP further highlight the outcomes obtained for the CED and the non negligible contribution of the embodied impacts. The 'cradle to grave' GPW of the intervention resulted equal to 24 kg CO_2-eq/m^2y. The emissions attributable to the operational stage accounted for the 82% of the total whereas the embodied carbon accounted for 16%, grouping the initial and recurring contributions.

The installation of the photovoltaic system, the insulation of external walls and of the attic resulted the first three hot spots in the embodied carbon assessment (see **Figure 21**); this result is also linked to the fact that these three interventions represented the most important ones in terms of surface involved and amount of materials employed. Moreover, the EPS insulation used for the traditional coat is a quite carbon intensive material.

Recurring embodied carbon makes a substantial contribution to the overall life cycle global warming potential (GWP) of the renovation. This contribution surpasses the impact associated with the initial renovation, primarily because it involves the replacement of all energy components and windows. The contribution of end-of-life phase was the least significant, making up about 2% of the total.

Quite different figures were obtained for the cost assessment with the initial investment stage (modules A1-A5) and the costs expected for future replacements of building components accounting for the 71% of the life cycle cost (see **Figure 26** and **Figure 27**).

The operational energy consumption (module B6) turned out to be the third contributor in the life cycle cost of the renovation with only the 28% of the global share. The end-of-life modules, that contribute 1% of the cost of the life cycle of the intervention, are of little importance.

A very expensive hot spot is represented by the insulation of the envelope both in terms of the amount of materials involved and also in relation to the number of working hours required during the design and realization of the intervention.

The difference in the results between LCC and LCA is caused by the fact that the first focuses on the economic aspects of the renovation, while the latter is concerned with its primary energy requirements and environmental impact. These two aspects can be related: for instance, improving energy efficiency can reduce both operational emissions and costs. However, they are not directly comparable because they measure different aspects of the renovation performance.

Life cycle costs include economic aspects that are not accounted by environment impact assessment methodologies. For instance, the intellectual work of engineers and architects in the design of the renovation or the labour of construction workers are accounted in the LCC but do not have a counterpart in the LCA. This kind of professional activities can have a high importance in innovative projects where high-skilled people are necessary for the realization of complex interventions.

Another cause can be ascribed to the current high level of prices of construction materials in Italy. Different authors (Casarin, 2021; De Masi et al., 2023) have already warned about the rebound in construction prices following the "Superbonus 110%" incentivization schemes in force in Italy ("Relaunch" Law Decree No. 34/2020).

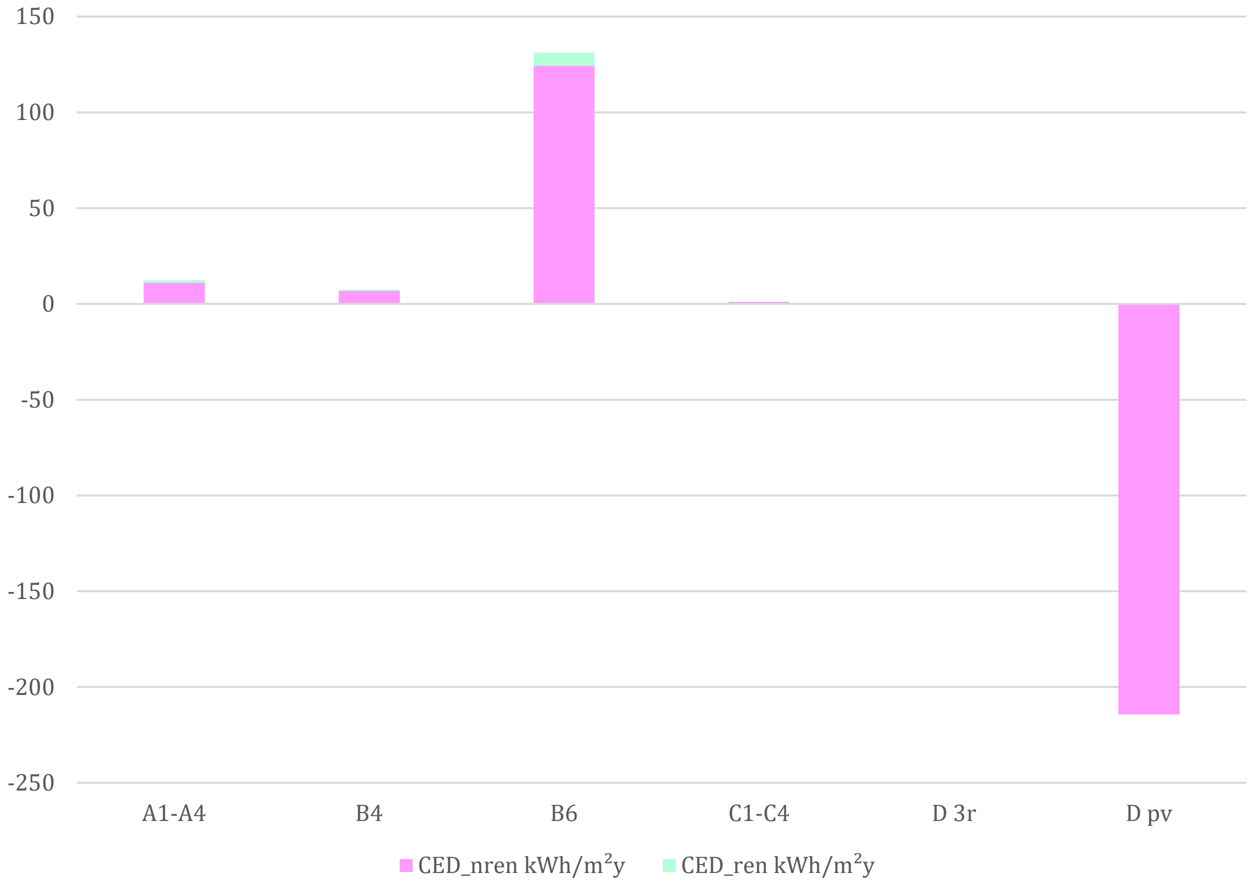


Figure 22. *Life cycle cumulative energy demand for the renovation in Povo.*

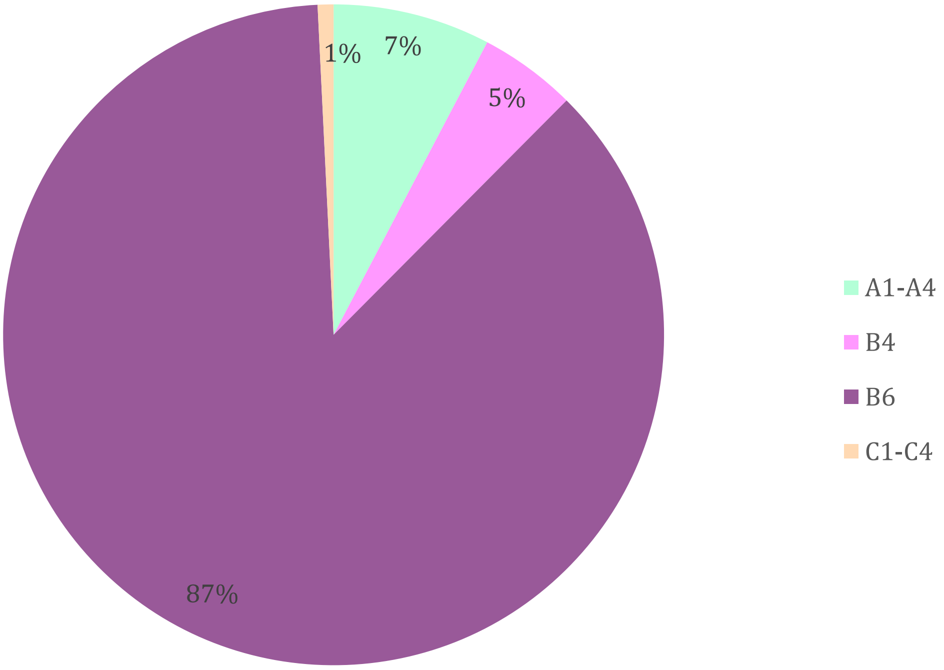


Figure 23. *Share of the different life cycle stages in the total non-renewable CED of the renovation in Povo.*

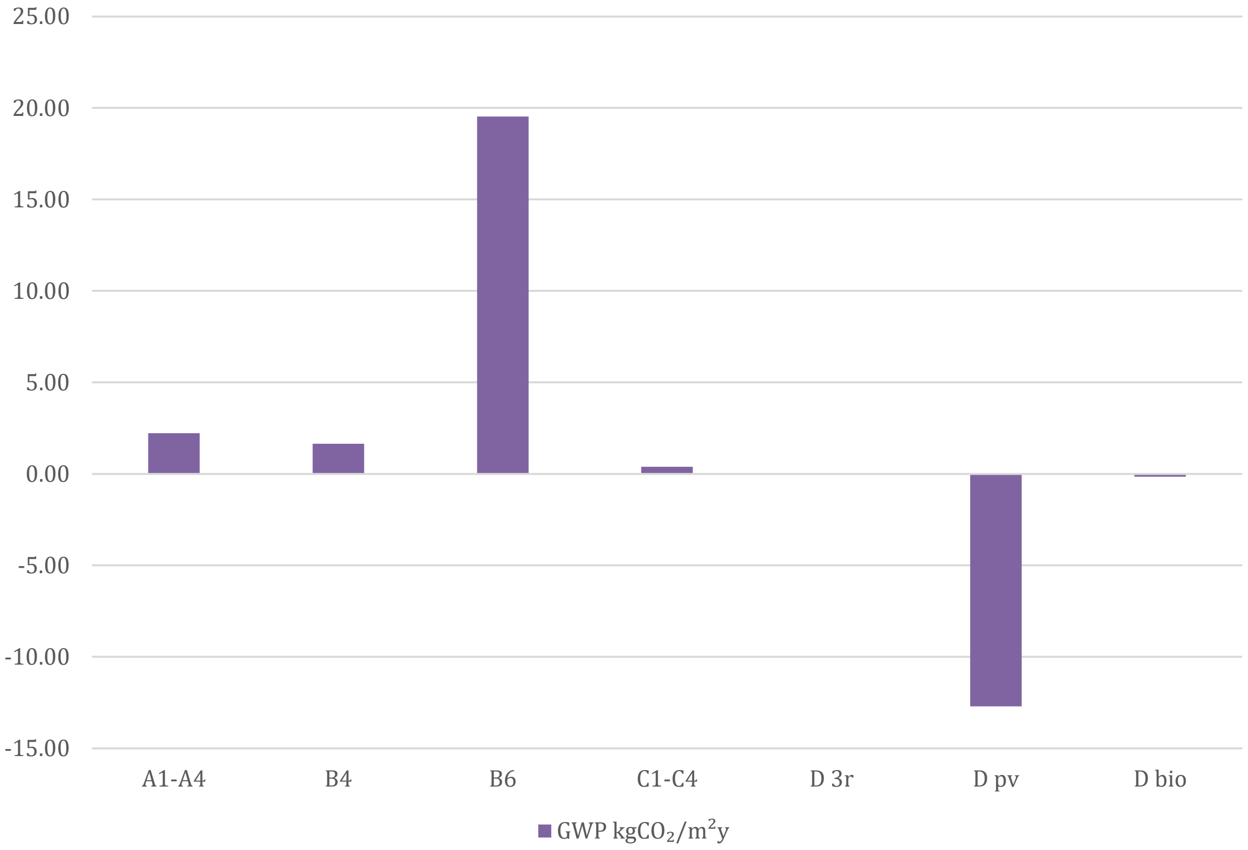


Figure 24. *Life cycle global warming potential for the renovation in Povo.*

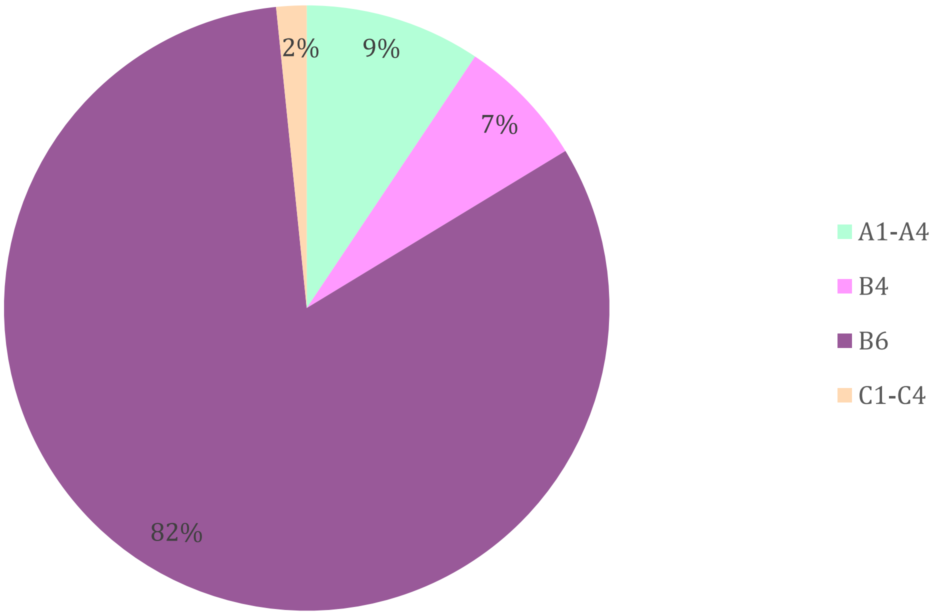


Figure 25. *Share of the different life cycle stages in the total GWP of the renovation in Povo (module D is excluded).*

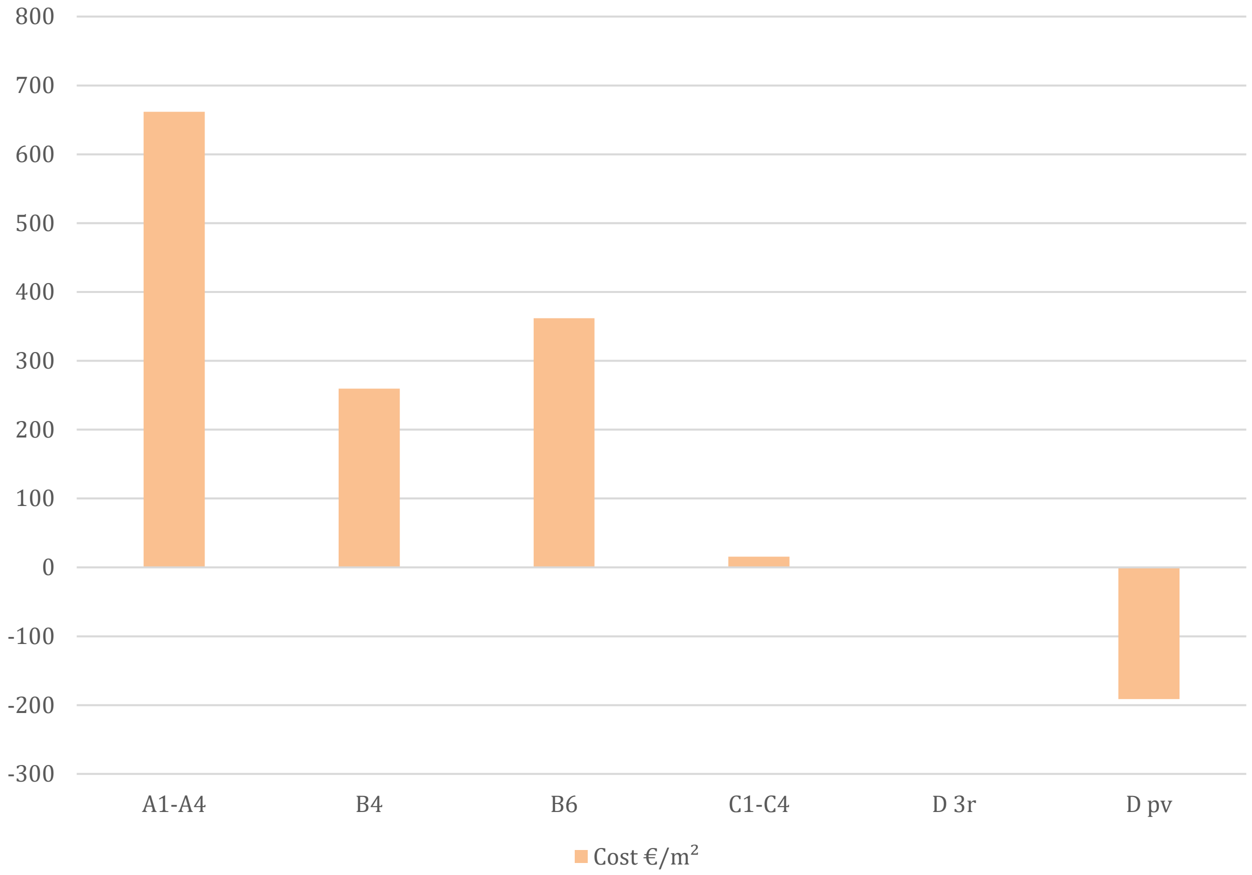


***Figure 26**. Life cycle costs for the renovation in Povo.*

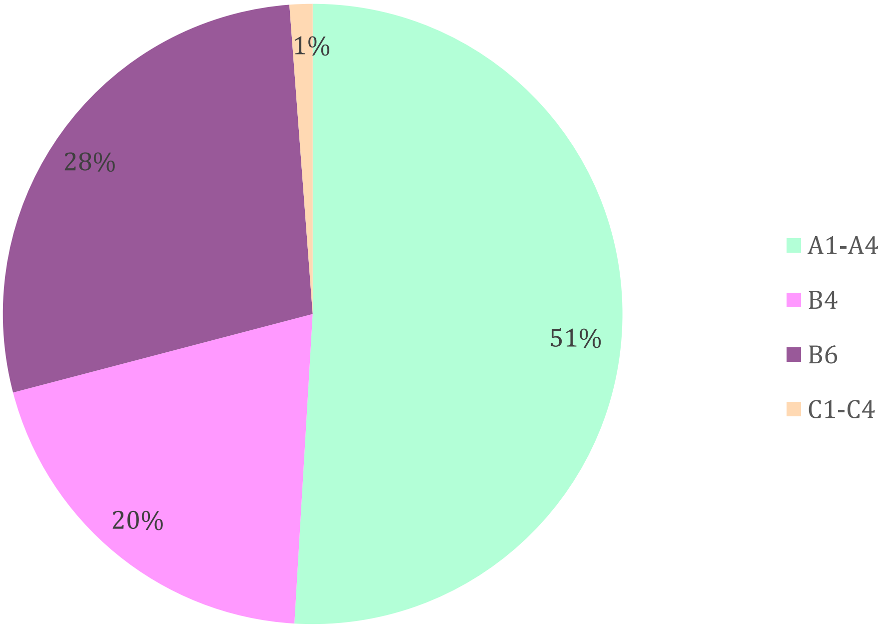


***Figure 27**. Share of the different life cycle stages in the total LCC of the renovation in Povo (module D is excluded).*

Scenarios assessment

Figure 28 presents the results related to the LCA of the design scenarios considered. As expected, the renovation decreased the environmental impacts of the building by about 61-63% if both the non-renewable CED and the GWP are respectively considered. This achievement is accomplished without considering the benefits linked to the renewable energy exportation, which increase the environmental friendliness of the intervention.

Looking at the costs assessment (**Figure 29**), instead, the renovation resulted in a slightly higher life cycle cost. This drawback is caused by the high investment and substitution costs. The uncertainty of the results is very high and different factors had or can have a detrimental or positive effect in the evaluation of the economic competitiveness of the intervention:

- Energy price fluctuations, due to the fact that the model adopted static energy prices
- Unforeseen increases in construction or renovation costs due to temporary market conditions
- Actual energy consumptions, which are expected to be different from the design estimation due to factors such as changes in occupancy, equipment use or users' behaviours.
- Degradation of the insulation performances of the insulation coating or of the photovoltaic panels

Specifically, the rise in energy costs, which is very likely given by current energy policies, could positively impact the economic competitiveness of the renovation project. Indeed, the combination of adverse conditions and limited growth in energy costs, can further reduce the expected return on investment for an energy renovation project. The current high costs of construction materials in Italy have a negative impact in the investment cost for the realization of the intervention. Generally, in energy retrofits, other factors can play a significant role in the life cycle cost performance of a building energy renovation project: high discount rates, for instance, can play a disadvantageous role, particularly when loans are involved in funding these improvements. These factors are not considered in the streamlined LCC approach implemented in this evaluation since it does not discount future cash flows and revenues. Nevertheless, the presence of incentives for energy renovation projects remains a very important driver for facilitating the implementation of the intervention in Povo.

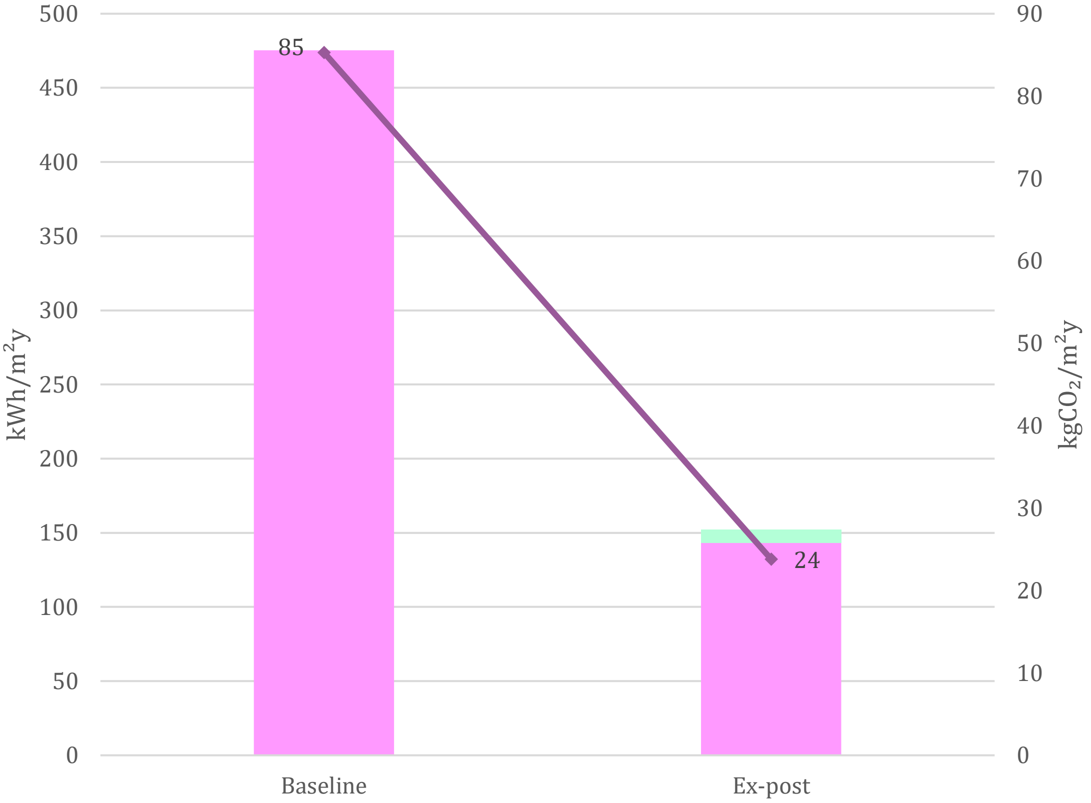


__Figure 28__. CED (lefts axis) and GWP (right axis) for the different renovation scenarios considered. (module D excluded)

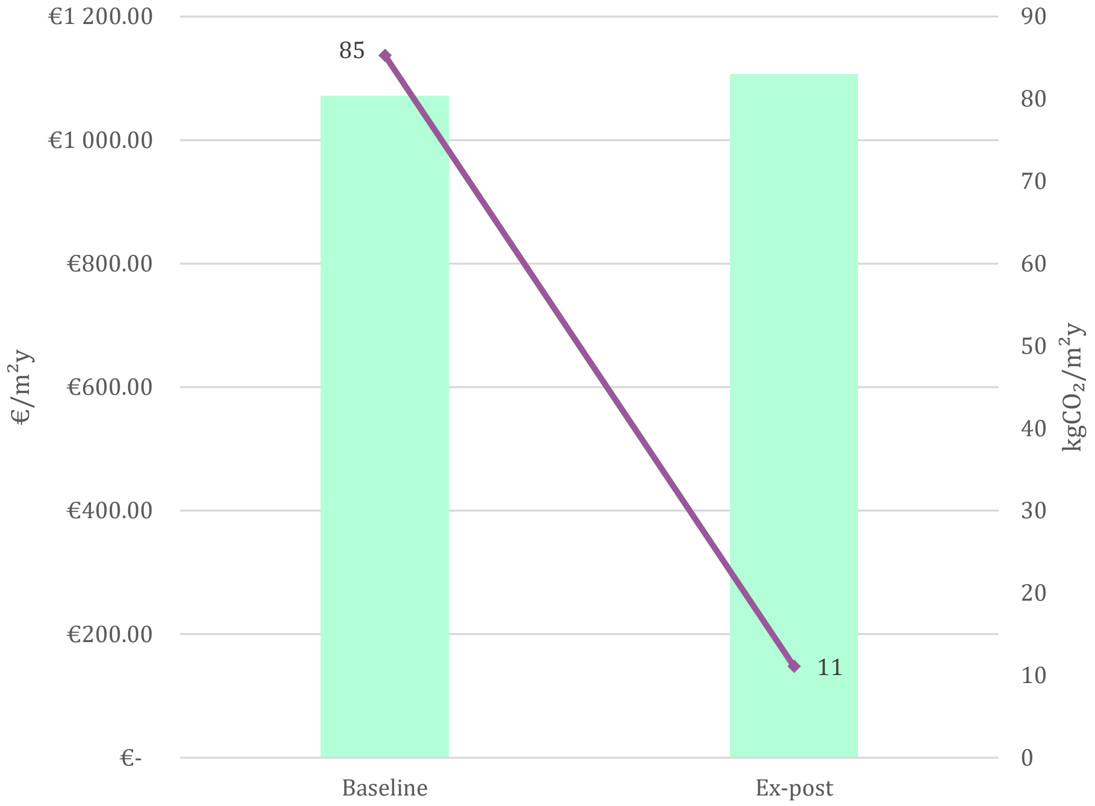


Figure 29*. LCC (lefts axis) and GWP (right axis) for the different renovation scenarios considered. (module D included)*

4.4.5. THE NEW BUILDING CASE STUDY

The new building consists of a multifunctional commercial building located in the ex-Zuffo car park in Piedicastello, a district of Trento. The area is located at 194 m.a.s.l. and the location is classified in the climatic zone F with 3001 heating degree days. The building is composed of a ground floor, a terrace and an underground level consisting of 315 m^2 of gross internal surface.

The building has been designed to be a plus energy building, then going beyond the energy efficiency and renewable energy coverage requirements imposed by the Italian legislation for new constructions.

Table 37*. Verification of minimum thermal transmittance requirements following the Italian legislation.*

Description	New building	Law minimum	Unit
U-value external walls (Renew-wall)	0.142	0.26	W/m^2K
U-value exterior roofs	0.132	0.22	W/m^2K
U-value exterior floors (terrace)	0.132	0.22	W/m^2K
U-value first floors (unheated rooms)	0.145	0.28	W/m^2K
U-value windows	0.85	1.00	W/m^2K
COP_{7-35} heat pump (air-water)	4.54	4.1	-

For instance, **Table 37** reports the verification of the minimum thermal transmittance of building components established by the Italian legislation.

On the energy systems front, the intervention involves the installation of a 10-panels photovoltaic power plant (about 3.65 kWp), installed on the roof of the building. This system is designed to meet the electrical consumption needs of the building for heating, cooling, DHW, lighting and ventilation. Additionally, the building will be equipped with a hybrid heat pump system exploiting both air and geothermal heat sources. Since the system is still under evaluation, a traditional aerothermal heat pump was considered in this assessment. Underfloor heating pipes working at 35°C were considered as emission systems.

The building was simulated using a semi-static code based on the technical specifications of UNI/TS 11300 series.

The simulated electricity consumptions of the building are reported in **Table 38**.

Table 38. *Verification of minimum thermal transmittance requirements following the Italian legislation.*

Description	**Electricity**	**Unit**
Heat pump consumption	5788	kWh/year
Lighting consumption	1466	kWh/year
Ventilation consumption	234	kWh/year
PV generation	7146	kWh/year

Figure 30 shows the monthly electricity balance of the building considering loads and PV generation. As it can be noted, the building has a positive energy balance from March to October meaning that the PV generation is higher than the electrical loads of the building, including absorptions of the heat pump, for lighting and ventilation.

Two design scenarios were considered:

- NZEB, which represents the baseline design solution.
- Plus-energy building, which is characterized by the maximization of the PV surface integrated in the building. Additional BIPV is installed on a canopy above the terrace, on the parapet of the terrace. The overall PV power is increased up to 16 kWp.

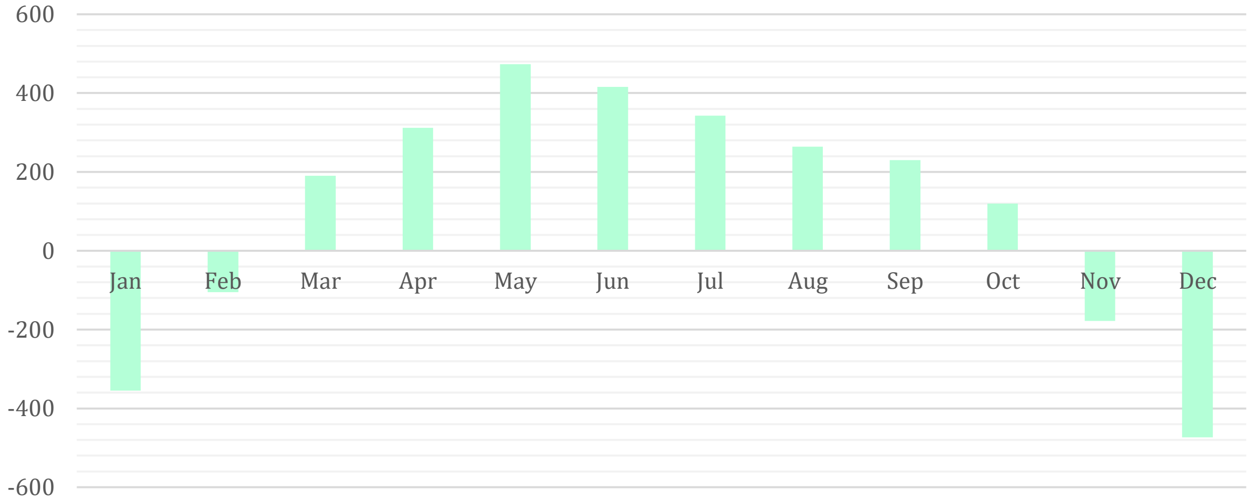


Figure 30*. Monthly balance [kWh] between load and generation of electricity (negative values imports higher than exports).*

4.4.6. NEW BUILDING: RESULTS

Figure 31 shows the components representing a hot spot for both the embodied GWP and non-renewable CED of the building. The first floor, underground walls, and foundation are all the components identified by an extensive utilization of concrete.
The primary energy requirement (kWh/m^{2}y) and the carbon dioxide equivalent emissions (kg CO$_2$-eq/m^{2}y) linked to various stages of the renovation life cycle are depicted in **Figure 32** and **Figure 34**, with their respective percentage contributions to the total shown in **Figure 33** and **Figure 35**.
The 'Cradle to gate' CED of the building is equal to 206 kWh/m^{2}y, of which 161 kWh/m^{2}y are covered by non-renewable sources. In relation to the non-renewable CED, the main outcome was the dominance of building operational energy use (module B6), with the non-renewable demand constituting approximately 77% of the total.
Embodied impacts (modules A1-A4) accounted for only 19% of the total, while the primary energy requirement associated with end-of-life was quite negligible, contributing for about 2% (**Figure 33**). Under the hypothesis done, namely that the sourcing of building materials is mostly local, the impacts and energy uses attributable to the transportation to the construction site (module A4) are quite negligible. Conversely, module B4 made a substantial contribution (2%) due to the necessity of substituting energy systems and windows in the building life cycle.
In terms of CED figures, it's noteworthy that the electricity generated by the photovoltaic system can save approximately all the operational non-renewable CED of the renovation, thus making its annual primary energy balance approximately zero.
Examining the GWP, a 'Cradle to gate' value of 17 kg CO$_2$-eq/m^{2}y was obtained. The findings regarding the GWP emphasize the significant role of embodied impacts. Emissions linked to the operational stage constituted only the 47% of the total, while embodied carbon accounted for 54%, encompassing both initial and recurring contributions. Due to the very low operational energy consumption of the building, the embodied components acquired an equivalent role in affecting the life cycle.
The installation of the foundation system, the first floor and the PV system emerged as the top three contributors in the embodied carbon assessment. This outcome is closely tied to the high use of concrete in foundations, basement walls and for the realization of the first floor. The substitution of concrete with Cross Laminated Timber in the upper floor, external walls and supporting frame, reduced the embodied GHG emissions of the above ground structures.
Recurring embodied carbon plays a substantial role in the overall GWP (5%) of the building due to the required substitution of energy systems and windows. In contrast, the contribution of end-of-life emissions resulted the lowest one, making up approximately 4% of the total.

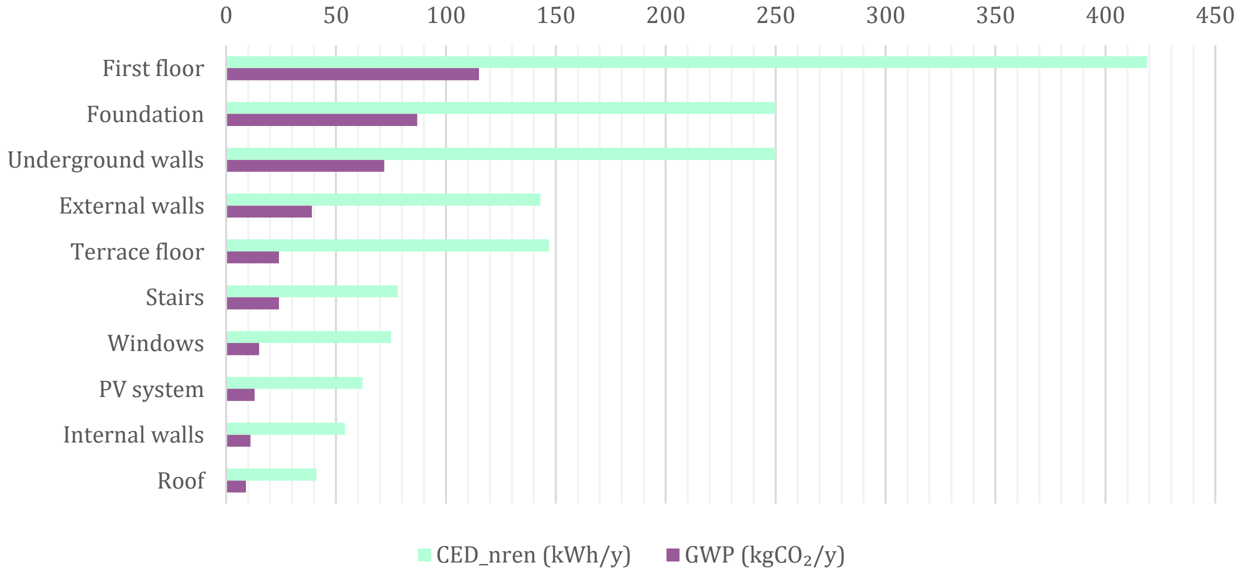


Figure 31. Hot spot analysis for the new building in Piedicastello.

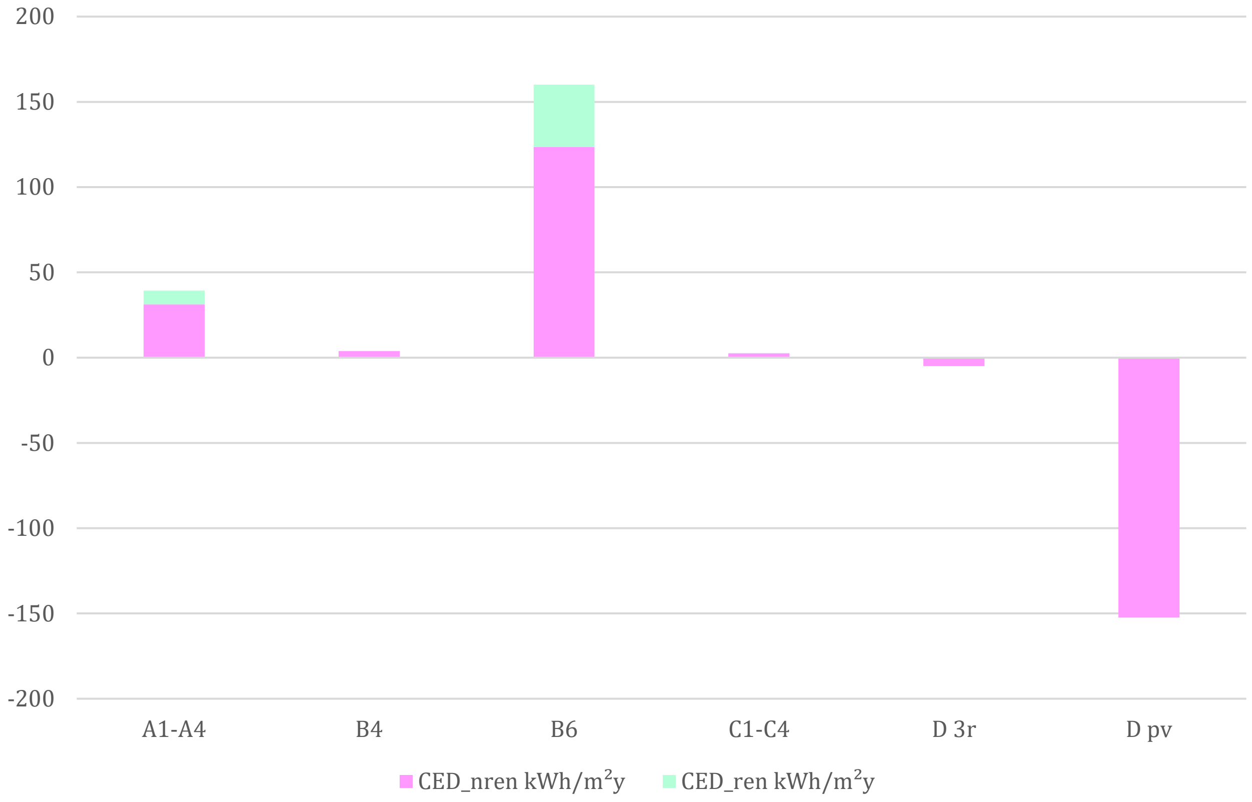


Figure 32. *Life cycle cumulative energy demand for the new building in Piedicastello.*

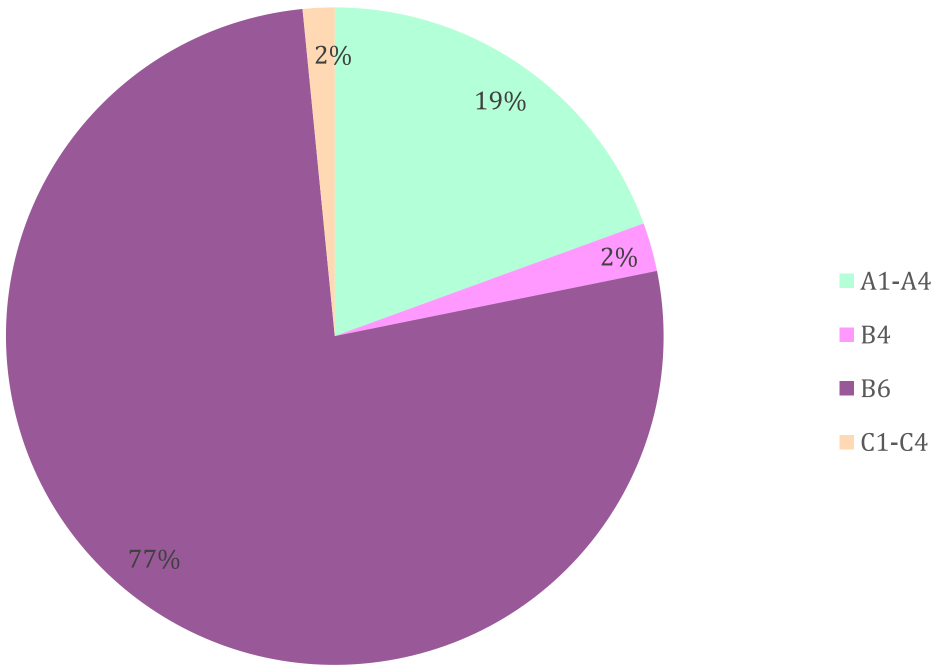


Figure 33. *Share of the different life cycle stages in the 'Cradle to Gate' non-renewable CED of the new building in Piedicastello.*

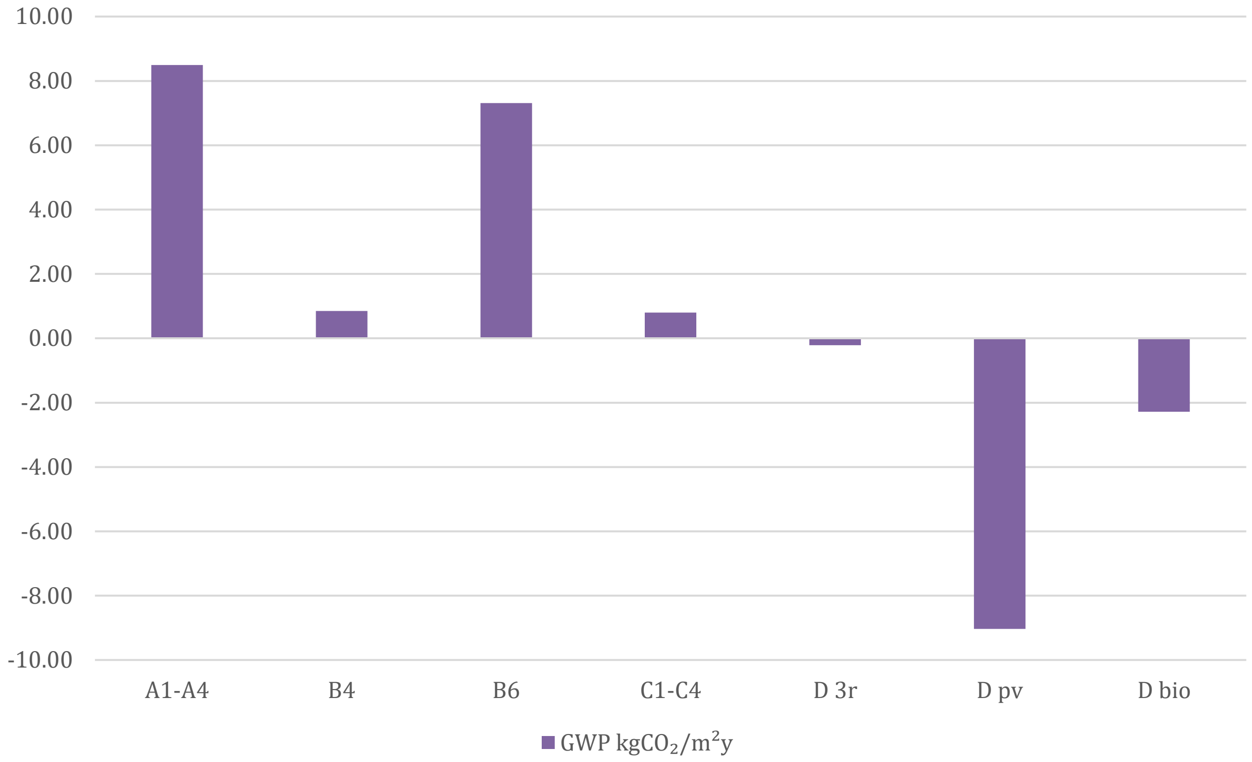


***Figure 34**. Life cycle global warming potential for the new building in Piedicastello.*

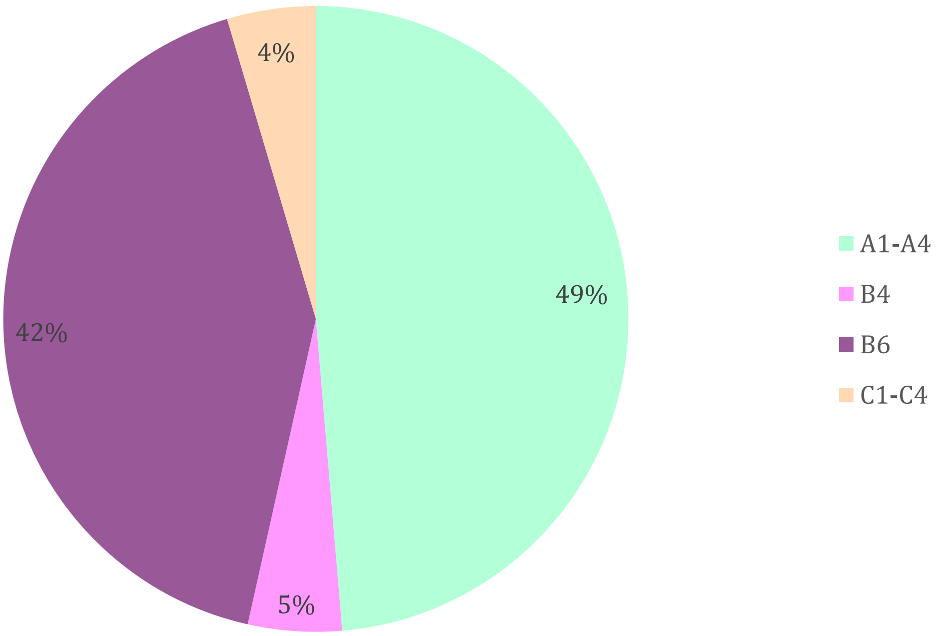


***Figure 35**. Share of the different life cycle stages in the 'Cradle to Gate' GWP of the new building in Piedicastello (module D is excluded).*

Scenarios assessment

Figure 36 illustrates the outcomes pertaining to the LCA of the considered design scenarios. The increase of the PV surface integrated in the building is expected to lead to a reduction of the energy resource use and climate change emissions of the building.

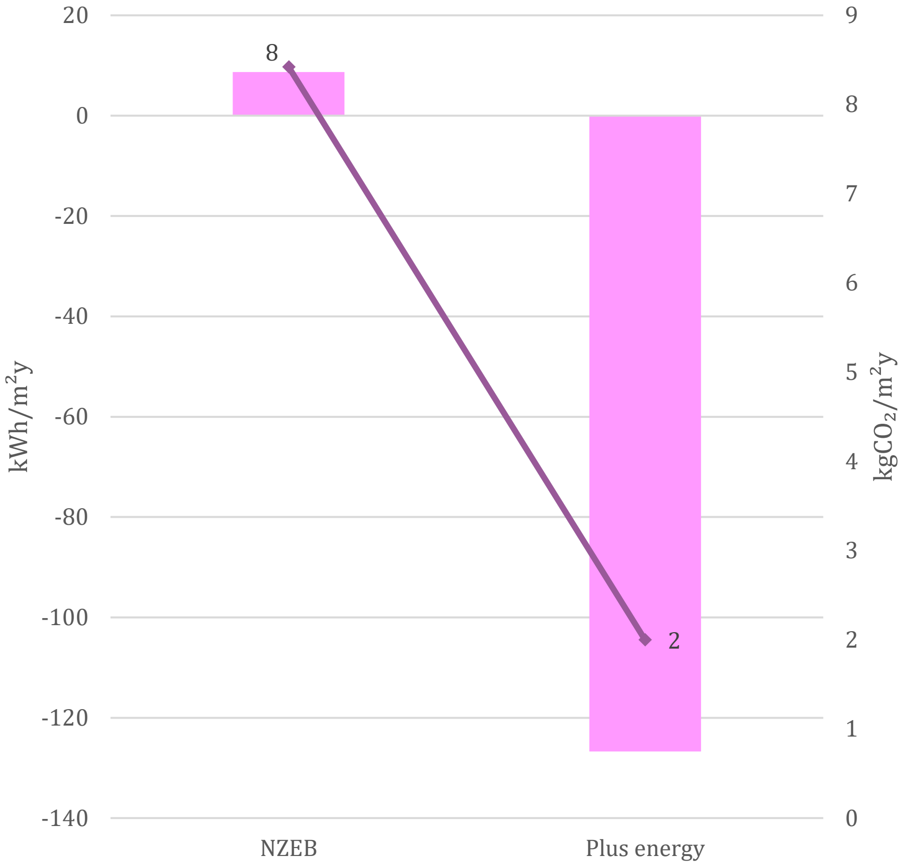


Figure 36. *CED (lefts axis) and GWP (right axis) for the different scenarios considered.*

4.5. UTRECHT DEMO

This chapter presents the assessment of the environmental and costs of the retrofitting of the Bredero buildings in the city of Utrecht. **Figure 37** shows a map with the four buildings indicated. The buildings, owned by the housing association Bo-Ex, consist of 65 apartments each one inhabited by tenants. The buildings were originally built in the 1970s and are currently in need of a renovation. **Figure 38** shows the current status of one of the Bredero buildings.

Bo-Ex offers over 9000 rental apartments in Utrecht built over several decades. The Dutch housing associations made agreements with the national government and municipality to make their building stock more sustainable and affordable. Also, they agreed to expand their stock to house more tenants. Specifically, Bo-Ex will work towards a CO_2-neutral environment and work towards climate adaptive and green neighbourhoods; and build and demolish circular. This relates to the ARV KPIs.
The steps Bo-Ex will take to reach the CO_2-neutral environment goal include insulation, especially of the apartments with an E, F or G label and collaboration with the municipality to move away from natural gas as an energy source for domestic heating. In relation to the circularity goal, Bo-Ex will apply circular building methods as much as possible in new constructions and pay attention during demolishment to withdraw materials from the building that can be re-used.
While committed to the environment, Bo-Ex is also committed to affordable housing for their tenants.

Therefore, the investment costs and total costs of ownership are important KPIs to Bo-Ex. For each renovation project, Bo-Ex makes a cost benefit analysis to decide the renovation level. Most apartments

are renovated to nearly zero energy buildings. However, for the Bredero buildings, Bo-Ex wants to take an additional step and aim for a positive energy building by a thorough retrofit.
This chapter analysis the design made to retrofit the Bredero buildings to positive energy buildings. It will evaluate the design using a life cycle analysis (LCA) and calculating the life cycle costs (LCC).

Figure 37. *We study the retrofitting of the Bredero buildings, at site 3, in Kanaleneiland.*

Figure 38. *Current condition of one of the Bredero building in the Utrecht demo.*

4.5.1. NZEB, PEB, LOW-E BUILDINGS: DEFINITIONS

Nearly zero energy building

Nearly zero energy buildings translate into BENG. The BENG has been mandatory for all new construction since January 2021. The demands follow from the Dutch energy agreement for sustainable development and the European Energy Performance of Buildings Directive (EPBD). For renovations, the BENG is not mandatory.

The energy performance of a building is evaluated in BENG using three indicators:

1. BENG 1: Maximal energy need for heating and cooling in kWh/m^{2}y. This indicator calculates the actual energy need, independent from the energy carrier and heating or cooling appliances used.
2. BENG 2: Maximal primary fossil energy usage, also in kWh/m^{2}y. The energy needed in BENG 1 results in energy usage from the grid or local energy production. This indicator shows the usage of primary fossil energy.
3. BENG 3: Minimal share of renewable energy in percent (%). This includes both electricity and other renewable energy, such as heat.

Figure 39 shows the relationship between the three indicators.

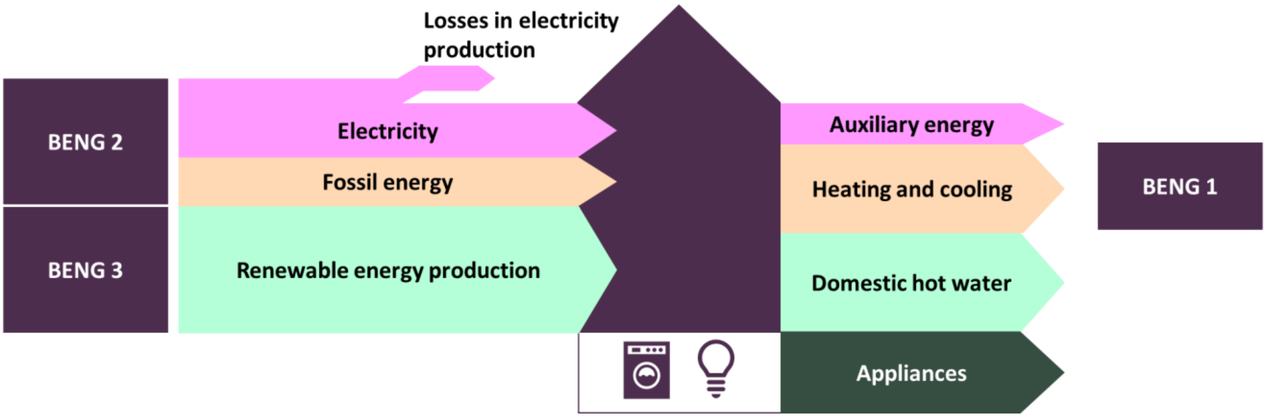


Figure 39. *Relation between Dutch demands on energy performance of new-built construction.*

The NTA8800 describes the terms, definitions and methods for determining the energy performance on each of these indicators (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2020). The demands per indicator are published by the National Government and shown in **Table 39**. The requirements distinguish between several levels of building compactness. The compactness factor is the ratio between the surface area of the building where the thermal energy is lost (A_{ls})and the floor area (A_g). For completeness the table includes all building types in the ARV demo sites across Europe.

For residential buildings the demands are to be met per building, so for multifamily homes, the demands are to be met for the complex as a whole. Still, they are to be reported per apartment as well. This is required for communication with the tenants or buyers. Furthermore, the apartments need to meet requirements on reduction of risk of overheating. The indicator used is the TO$_{\text{juli}}$ which counts the times the maximum temperature is exceeded. Finally, the building needs to have an energy label upon delivery (Rijksdienst voor Ondernemend Nederland, 2023a).

Table 39. *Dutch demands for NZEB-buildings (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019).*

Type	**BENG 1: Energy need (kWh/m^2y)**		**BENG 2: Primary energy usage (kWh/m^2y)**	**BENG 3: Renewable energy (%)**
	Compactness: A_{ls}/A_g	demand		
Multifamily	$A_{ls}/A_g \le 1.83$	≤ 65	≤ 50	≥ 40 %
	$1.83 < A_{ls}/A_g \le 3.0$	$\le 55 + 30 * (A_{ls}/A_g - 1.5)$		
	$A_{ls}/A_g > 3.0$	$\le 100 + 50 * (A_{ls}/A_g - 3.0)$		
Single family	$A_{ls}/A_g \le 1.5$	≤ 55	≤ 30	≥ 50 %
	$1.5 < A_{ls}/A_g \le 3.0$	$\le 55 + 30 * (A_{ls}/A_g - 1.5)$		
	$A_{ls}/A_g > 3.0$	$\le 100 + 50 * (A_{ls}/A_g - 3.0)$		
Offices	$A_{ls}/A_g \le 1.8$	≤ 90	≤ 40	≥ 30 %
	$A_{ls}/A_g > 1.8$	$\le 90 + 30 * (A_{ls}/A_g - 1.8)$		
Education	$A_{ls}/A_g \le 1.8$	≤ 190	≤ 70	≥ 40 %
	$A_{ls}/A_g > 1.8$	$\le 190 + 30 * (A_{ls}/A_g - 1.8)$		
Health care without bedding	$A_{ls}/A_g \le 1.8$	≤ 90	≤ 50	≥ 40 %
	$A_{ls}/A_g > 1.8$	$\le 90 + 35 * (A_{ls}/A_g - 1.8)$		

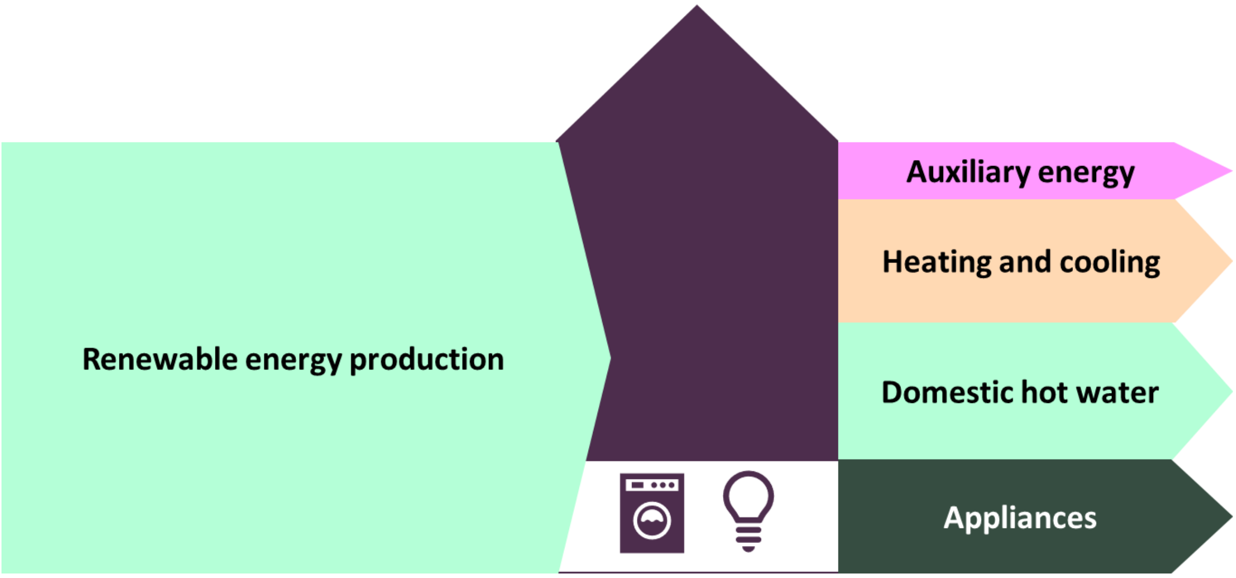


Figure 40. *In a NOM building, there is a yearly balance in the renewable energy produced and the energy used for the building-related energy and the appliances in the building. The energy meter reads zero after a year.*

Table 40. *Energy performance requirements for the EPV, part of the NOM certificate (Rijksdienst voor Ondernemend Nederland, 2023b).*

I	II	III	IV	V	VI	
EPV class	Compactness (A_{loss}/A_{ground})	Demand for space heating in kWh/m^2/year (BENG 1 indicator)	Design requirement: Primary (fossil) energy usage in kWh/m^2/year (BENG 2 indicator)	Sustainable electricity generated for household usage	Maximum EPV fee in €/m^2/month	
EPV Basic					Houses built before 2019	Houses built for 2019 onward
Single-family home	<1	≤43	≤0	>0	€1,25	-
	≥1	≤43+ 40 * (A_{loss}/A_{ground} – 1)				
Apartment	<1	≤45	≤0	>0	€1,25	-
	≥1	≤45+ 45 * (A_{loss}/A_{ground} – 1)				
EPV High Quality (hoogwaardig)					Houses built before 2019	Houses built for 2019 onward
Single-family home	<1	≤30	≤-30	>2100	€1,65	€1,15
	≥1	≤30+ 20 * (A_{loss}/A_{ground} – 1)				
Apartment	<1	≤30	≤-10	>530	€1,40	€0,90
	≥1	≤30+ 20 * (A_{loss}/A_{ground} – 1)				

Positive energy building

The builders that want to go beyond the legal requirements, may choose to build a NOM (Nul-op-de-meter: zero on the meter) house. Zero on the meter implies that the ingoing and outgoing energy add up to zero after a year. This includes both the building-related energy usage, for heating, cooling and hot tap water and the energy for appliances and lighting. **Figure 40** shows this balance. The building-related energy used is calculated using the NTA8800 under standard Dutch climate conditions and the energy for appliances is linked to the national average usage. The energy is produced after the meter, for example using solar panels. The energy production and energy usage don't have to be simultaneous, a yearly balance suffices.

The energy performance requirements for NOM are based on the requirements of the EPV. EPV (Energieprestatievergoeding) is a fee paid by social housing tenants to the housing corporation as a compensation for the investments to renovate the building to be energy positive. The fee should not exceed the reduction in energy costs experienced after the renovation compared to the period before the renovation.

The national government dictates energy performance criteria for the EPV. A new law is in the making that creates two levels of energy performance criteria. In addition to the current “high-quality level”, a new “basic level” is formulated. **Table 40** shows the requirements for the two levels. In the basic level only the building-related energy usage needs to be generated locally, while the high-quality level matches the NOM requirements.

The criteria match the BENG indicators 1 and 2. The sustainable electricity generated for household usage is the amount of generated electricity that needs to remain after the building-related energy demand is met. This electricity is intended for appliances and lighting.

The criteria for apartments are lower than the requirements for single-family houses. This was done to make the renovation of high-rise apartment buildings more attractive. A high-rise apartment building offers a reduced façade and roof surface to generate electricity with solar panels compared with single-family homes.

The NOM Keur certificate ensures the energy performance and quality of a NOM house. The certificate tests the house on proposition, application and lifetime. This includes the energy performance criteria but also looks for example at communication with the inhabitants, privacy, construction process, safety and plants and animals in the surroundings.

Table 41. *Insulation standard for renovation (Rijksdienst voor Ondernemend Nederland, 2023c).*

Building type	**Compactness (A_{ls}/A_g)**	**Net demand for space heating (kWh/m^2/year)**
Single-family homes, built before 1945	< 1.00	≤ 60
	≥ 1.00	≤ 60 + 105 * (A_{ls}/A_g – 1.0)
Single-family homes, built after 1945	< 1.00	≤ 43
	≥ 1.00	≤ 43 + 40 * (A_{ls}/A_g – 1.0)
Multifamily homes, built before 1945	< 1.00	≤ 95
	≥ 1.00	≤ 95 + 70 * (A_{ls}/A_g – 1.0)
Multifamily homes, built after 1945	< 1.00	≤ 45
	≥ 1.00	≤ 45 + 45 * (A_{ls}/A_g – 1.0)

Positive energy building

A positive energy building generates more electricity than it uses. A NOM building will often meet these criteria, as NOM guarantees at least energy neutrality. Therefore, the design will often be energy positive.

An energy concept that guarantees energy positiveness is a passive house. This concept includes an energy certificate that ensures the building uses less than 15 kWh/m^2y for space heating. The primary energy usage is limited at 120 kWh/m^2y. The national Passiefhuis Stichting issues certificates for passive houses.

Low energy building for renovation

The BENG is mandatory only for new constructions. For renovations, the government does not enforce any energy performance level in general. However, the government requires all the rental houses to meet the so-called insulation standard by 2050. This standard sets a maximum net energy demand for space heating (BENG 1 indicator), see **Table 41**. Private homeowners are encouraged to meet these criteria as well.

4.5.2. METHODOLOGY

This section describes the methodology for the life cycle analysis and life cycle costs analysis. Both the analyses use the buildings surface area. This is the gross heated area of the buildings. Both analyses assume the retrofit will start in 2025 and the retrofitted building will be exploited for 50 years. During these 50 years, the building is maintained and installations that reach their end of life are replaced. After 50 years the building will be demolished.
The burden-free approach is adopted, as described in *3.1.4. Allocation approaches in building renovations* and in accordance with the other demo cases described in this report.

Energy analysis

Both the analyses require the operational energy demand as an input. Therefore, this section starts with a description of the energy analysis. The energy analysis was done using the Uniec3 software. This software calculates the energy usage according to the Dutch standard NTA8800. This is the standard for all energy performance calculations for building permits (BENG, see 4.5.1. NZEB, PEB, Low-e buildings: definitions).

Energy analysis will give the building-related energy demand, as well as the demand for appliances and lighting. The energy for appliances and lighting is assumed 2100 kWh/apartment, based on the Dutch national average demand. Furthermore, it gives the expected electricity production by the PV-system. These results serve as an input to the LCA and LCC calculations.

The number of solar panels was undecided in the design. The energy analysis showed the energy demand, and the number of panels was chosen to meet this demand. The energy production was maximized by applying 950 m^2 of solar panels on the roof and 146 m^2 on the south-west façade. As the building is designed to be a positive energy building, the production of the panels should cover both the building-related and household demand. This criteria is not met with these PV area, however, the building offers no south-facing surface to increase the production.

The retrofitted building will generate electricity using solar panels. The production and consumption of electricity is not simultaneous. Based on measurements and calculations of a previously retrofitted building with the same concept (Henriette Dreef), we assume 35% of the electricity to be used directly, while 65% of the electricity is delivered to the grid. This percentage is applied both to building-related and household electricity demand. The building gets electricity from the grid when the PV panels cannot meet the demand.

LCA analysis

The LCA analysis was done using the GPR software, from W/E advisers. This software is based on the Dutch determination method for environmental impact analysis (Stichting Bouwkwaliteit, 2019). This determination method is based on the European standard EN 15804 for Environmental Product Declarations – EPD. The Dutch determination method completed the standard for the Dutch context. (ISO82.5). The GPR uses the product declarations from the Dutch Environmental Database (NMD). For this project the declarations as present at 12-12-2023 were used.
The GPR software includes all life cycle phases, as shown in **Table 42**.

Table 42. *Life cycle modules considered for the LCA analysis of the Dutch case study.*

LCA module	**Description**	**Included**
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	✓
B1	Use	✓
B2	Maintenance	✓
B3	Repair	✓
B4	Replacement	✓
B5	Refurbishment	✓
B6	Operational energy use	✓
B7	Operational water use	✓
C1	Demolition, de-construction	✓
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	✓
	Renewable energy production	✓
	Biogenic carbon	✓

The cumulative energy demand entails both the embodies energy in the materials used and the energy for operations. The effect of the embodied energy is spread along the lifetime of the building, that is 50 years. The operational energy is calculated for one year of operation.

The emissions for electricity usage from the grid are assumed 0.30 kg CO_2/kWh, the Dutch CO_2-emission factor of 2021, integral method (CBS, 2023). The emission factor is expected to reduce in time as the electricity production includes more renewable sources, but this is not part of this analysis. The production from the PV solar panels is taken into the calculations as negative emissions, with an emission factor equal to the factor of usage.

In the cumulative energy demand a distinction will be made between renewable and non-renewable energy. The embodied energy is calculated by the GPR software based on product declarations from the Dutch Environmental Database. Therefore, we base the use the Product Declaration for electricity from the grid to make the distinction in operational energy. This declaration states 27% of the Dutch electricity is renewable.

Table 43. *Included life cycle stages in the LCC calculation for the Dutch demo case.*

LCC module	Description	Included
A1	Raw material extraction and processing	✓
A2	Transport to the manufacturer	✓
A3	Manufacturing process	✓
A4	Transport to the building site	✓
A5	Installation in the building site	✓
B1	Use	✓
B2	Maintenance	✓
B3	Repair	✓
B4	Replacement	✓
B5	Refurbishment	✓
B6	Operational energy use	✓
B7	Operational water use	✓
C1	Demolition, de-construction	✓
C2	Transport to waste treatment facilities	✓
C3	Waste processing	✓
C4	Disposal	✓
D	Reuse, recovery or recycle potential	✓
	Renewable energy production	✓
	Biogenic carbon	✓

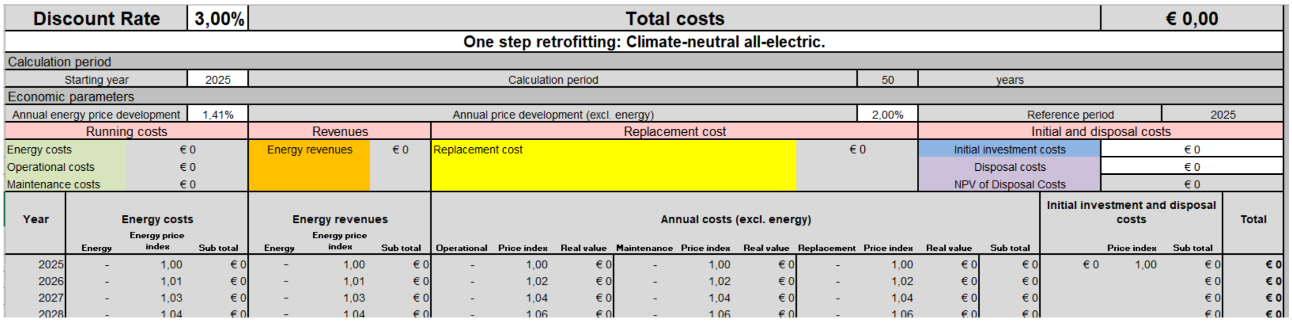
LCC analysis

The life cycle cost analysis was done using an excel spreadsheet developed for ARV, see **Figure 41**. This spreadsheet includes the costs of the life cycles as shown in **Table 43**. This spreadsheet calculates the total costs based on Net Present Value, in accordance with European Commission regulation 244/2012.

In the life cycle cost analysis, we made the following assumptions. We have taken the 2025 electricity price from the Dutch Climate and Energy Report, KEV (Planbureau voor de Leefomgeving, 2021) and an annual price development from EU guidelines (European Commission, 2012). Other prices are assumed to develop by 2% annually. The discount rate is set at 3%. All prices are including VAT. The burden-free approach was applied, meaning that the disposal costs of the existing building at the end of the exploitation period are excluded from the calculations.

The costs and revenues per kWh electricity from and to the grid are asymmetric. The costs are based on the mean kWh prices within EU, all taxes and levies included. Revenues are based on the mean kWh prices within EU, taxes and levies excluded. Dynamic price movements during the day are not included.

The results of the LCC analysis are compared to an LCC calculation based on the local practice in alignment with the ARV KPIs. The reference scenario for the local practise is a two-step retrofitting. This means an initial renovation in 2025 only including strict necessary items to meet the label criteria for rentals, see the section on Low energy building for renovation on page 94. This initial renovation is followed by a second renovation to a climate-neutral all-electric building in 2035.



Discount Rate	3,00%	Total costs	€ 0,00

One step retrofitting: Climate-neutral all-electric.

Calculation period
Starting year 2025 | Calculation period 50 years

Economic parameters
Annual energy price development 1,41% | Annual price development (excl. energy) 2,00% | Reference period 2025

Running costs		Revenues		Replacement cost		Initial and disposal costs	
Energy costs	€ 0	Energy revenues	€ 0	Replacement cost	€ 0	Initial investment costs	€ 0
Operational costs	€ 0					Disposal costs	€ 0
Maintenance costs	€ 0					NPV of Disposal Costs	€ 0

Year	Energy costs			Energy revenues			Annual costs (excl. energy)										Initial investment and disposal costs			Total
	Energy	Energy price index	Sub total	Energy	Energy price index	Sub total	Operational	Price index	Real value	Maintenance	Price index	Real value	Replacement	Price index	Real value	Sub total		Price index	Sub total	
2025	-	1,00	€ 0	-	1,00	€ 0	-	1,00	€ 0	-	1,00	€ 0	-	1,00	€ 0	€ 0	€ 0	1,00	€ 0	**€ 0**
2026	-	1,01	€ 0	-	1,01	€ 0	-	1,02	€ 0	-	1,02	€ 0	-	1,02	€ 0	€ 0			€ 0	**€ 0**
2027	-	1,03	€ 0	-	1,03	€ 0	-	1,04	€ 0	-	1,04	€ 0	-	1,04	€ 0	€ 0			€ 0	**€ 0**
2028	-	1,04	€ 0	-	1,04	€ 0	-	1,06	€ 0	-	1,06	€ 0	-	1,06	€ 0	€ 0			€ 0	**€ 0**

Figure 41. *Excel spreadsheet to calculate life cycle developed for ARV.*

4.5.3. THE DUTCH CASE STUDY

Renovation in Utrecht

This section investigates the performance of the planned renovation of the Bredero apartment buildings in Kanaleneiland. We assume the retrofit as proposed by Inside Out to be a positive energy building, fit for EPV High Quality.

For this analysis we received detailed building plans from the Bos group. However, the design is not completed, as Bo-Ex's plans for the renovation are not finished either.

The design for the Bredero does not meet the PEB-requirements. The electricity generation from the PV solar system covers the building-related energy demand, but the generation is inadequate to cover the household electricity demand as well. It meets the requirements for NZEB. This is due to the new design requirements. In our definition of a positive energy building, a building is better than NOM (nul-op-de-meter). NOM requires local energy generation to cover both the building-related and household energy usage (see **Figure 40**). The amount of solar panels was calculated according to this requirement of energy neutrality. However, the design criteria changed during the design process. To the owner and housing association Bo-Ex meeting the EPV-requirements is leading in the design. The EPV-requirements were in line with the NOM-requirements; however, a new law changed the EPV-requirements for multi-family housing. For multi-family housing the generation of only 520 kWh/household is required, as shown in **Table 40**.

LCA results

The carbon dioxide equivalent emissions (kg CO_2-eq/m^{2}y) and cumulative energy demand (kWh/m^{2}y) associated with the different phases of the life cycle of the retrofitted building are presented in **Figure 42**, **Figure 44** and **Figure 45**. The total GWP of the retrofit is -1.8 kg CO_2-eq/m^{2}y. The relative contribution to the total is displayed in **Figure 43** and **Figure 46**.

As the figure show, the B6 phase, operational energy use, make up the main part of the global warming potential and cumulative energy demand of the retrofitted building. This is compensated by the generated energy, in phase D.

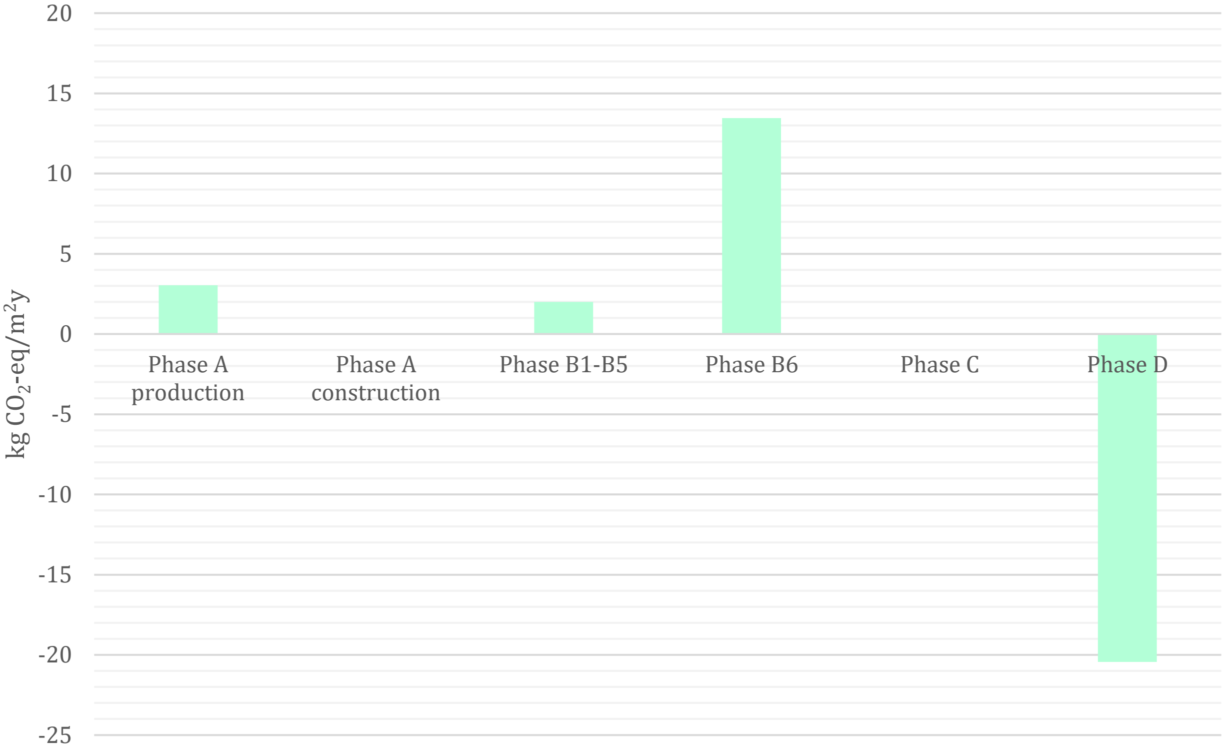


Figure 42. *Life cycle global warming potential (100 years) for the retrofit in Utrecht. Only the building-related energy is included in the figure.*

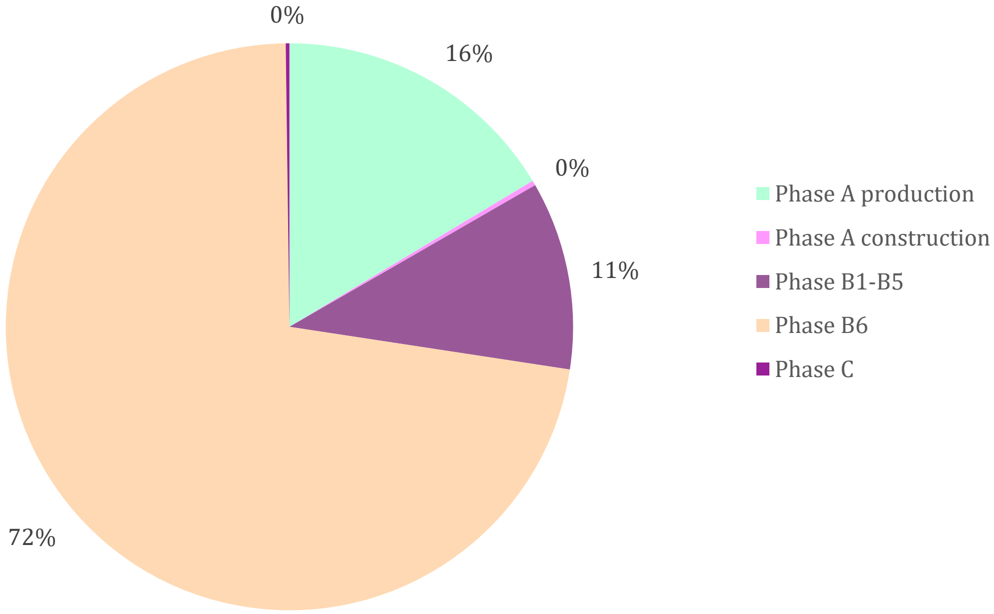


Figure 43. *Share of the different life cycle stages in the total GWP-100y of the retrofit in Utrecht (module D is excluded). Only the building-related energy is included in the figure.*

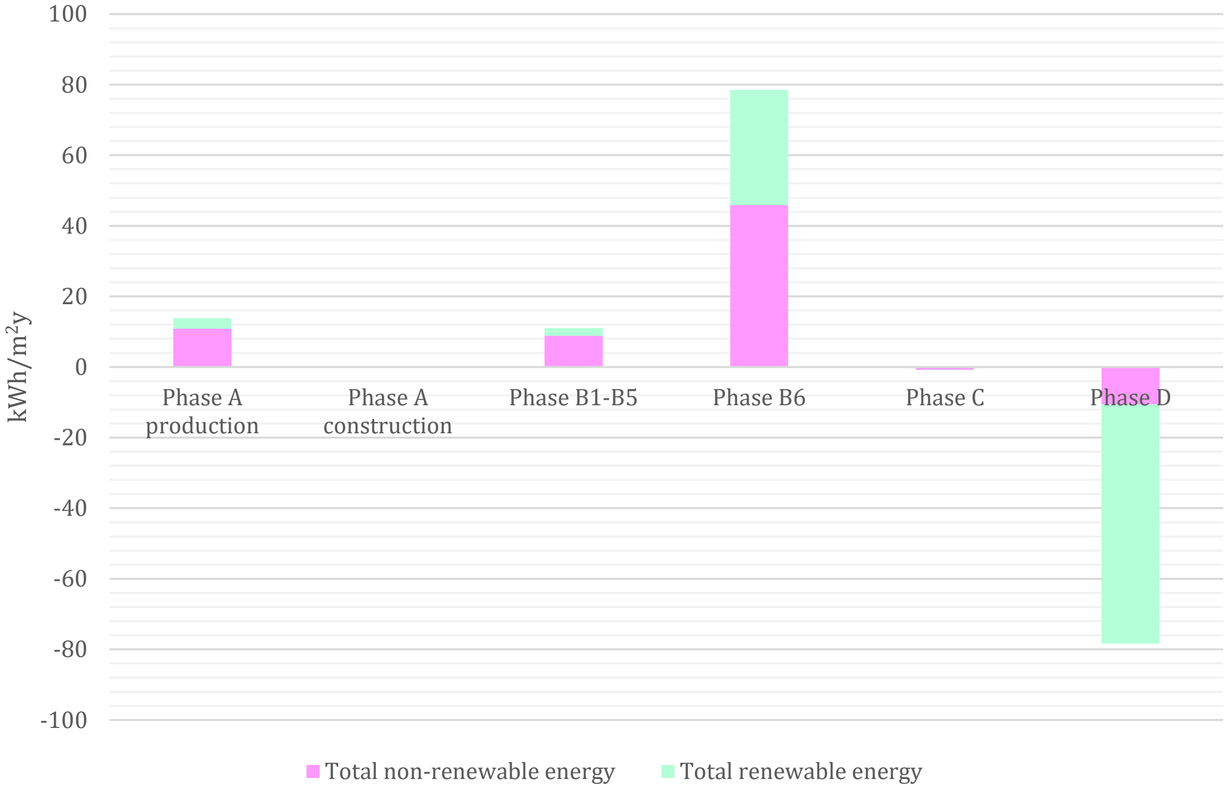


Figure 44. *Cumulative energy demand for the Bredero retrofit in renewable and nonrenewable energy usage including household energy usage.*

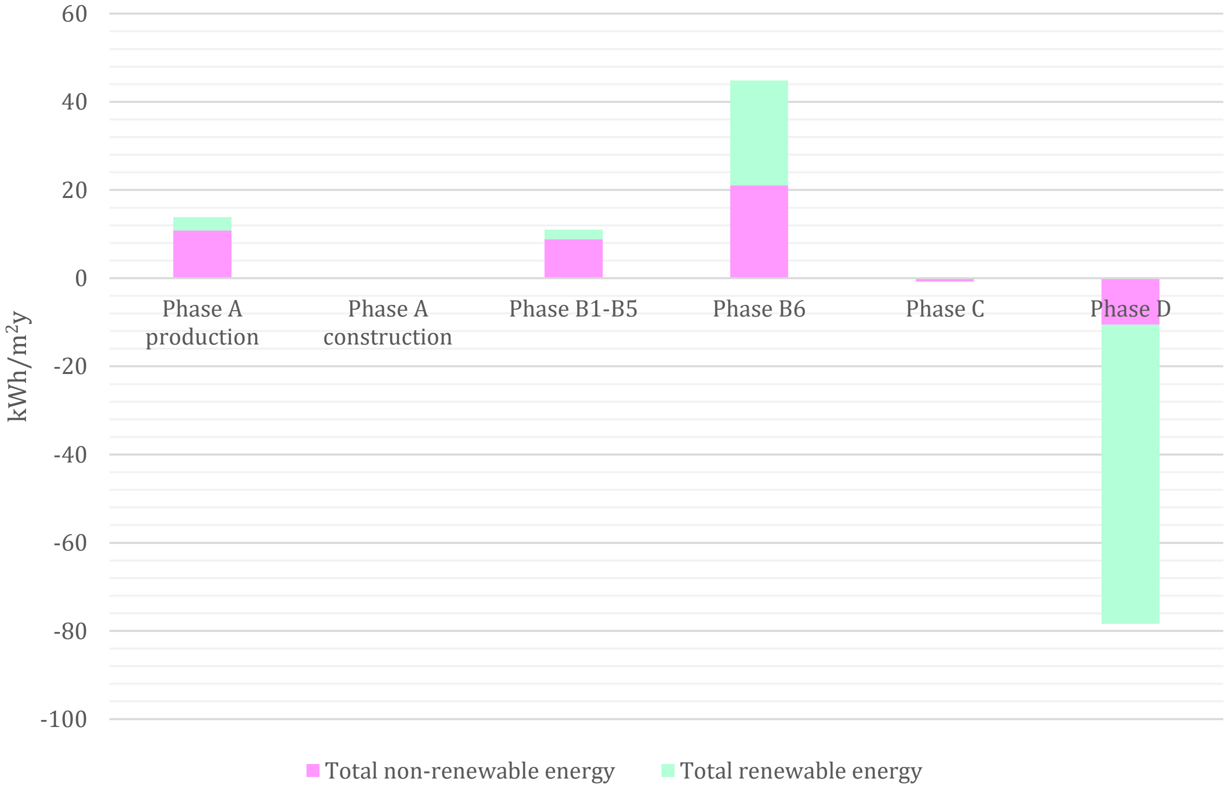


Figure 45. *Cumulative energy demand for the Bredero retrofit in renewable and nonrenewable energy usage excluding household energy usage.*

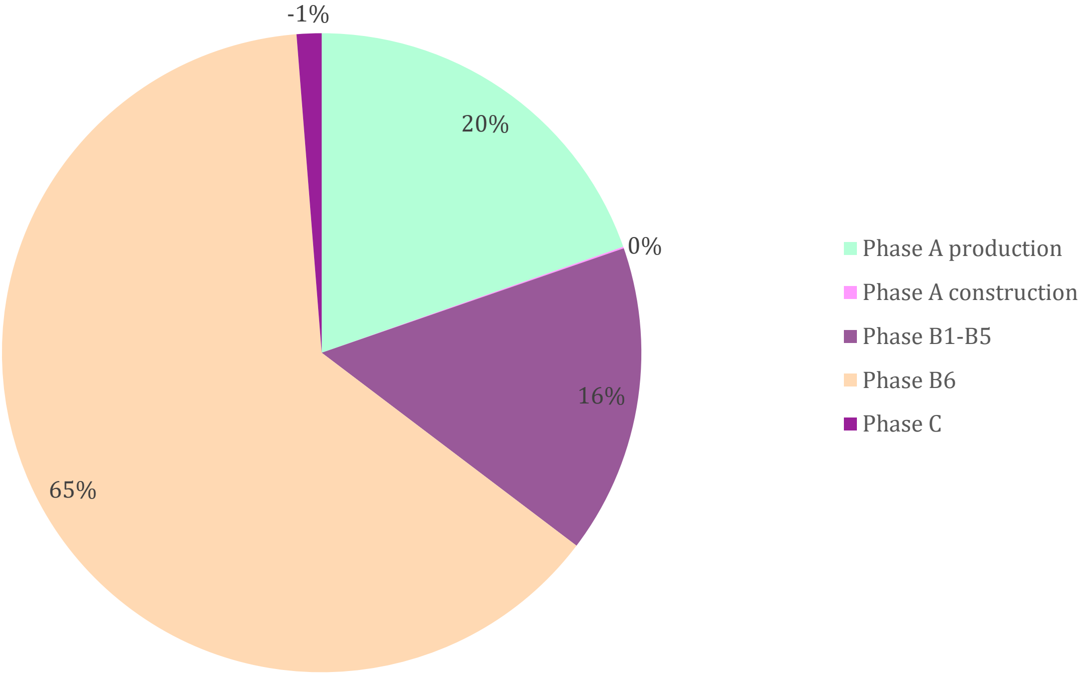


Figure 46. *Share of the different life cycle stages in the total CED of the renovation in Utrecht (module D is excluded). Only the building-related energy is included in the figure.*

The environmental impact of the separate building components added in the renovation is shown in **Figure 47**. The climate impact of the electrical systems is the largest. This section includes all the solar panels, both on the roof and the south-west facade. This is in line with LCA results from other retrofits. The façade panels have the second biggest impact. The façade panels make up the largest amount of materials used as well. The climate installations, including the convectors and the heat pump only make up 1% of the total climate impact.

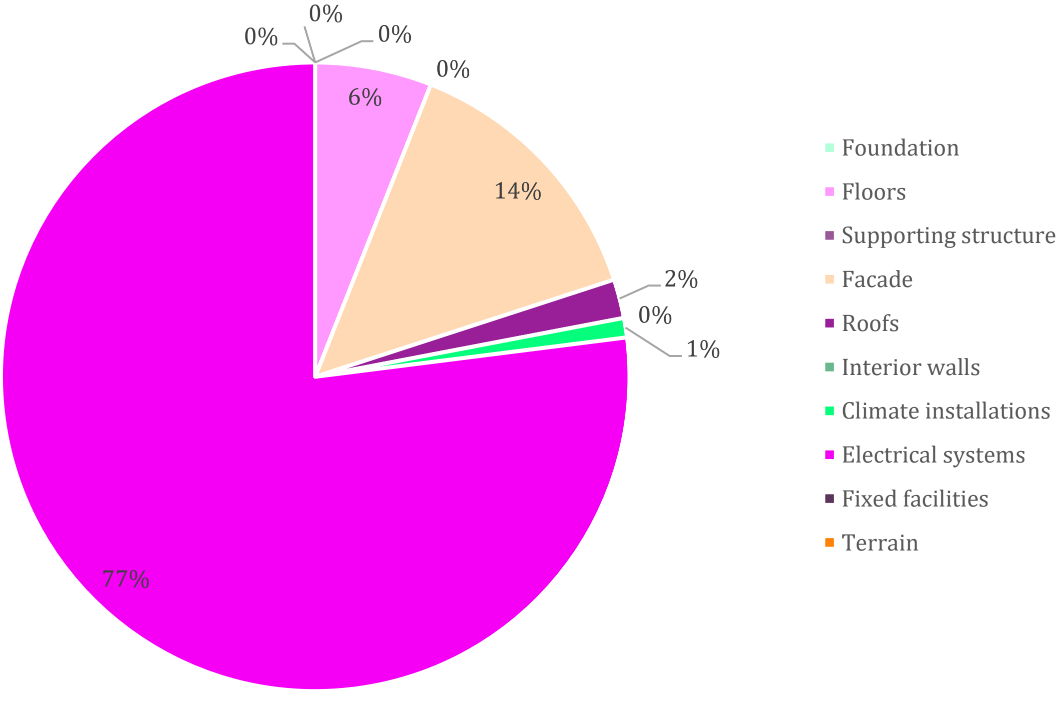


Figure 47. *Contribution of the components to the total environmental impact of the renovation.*

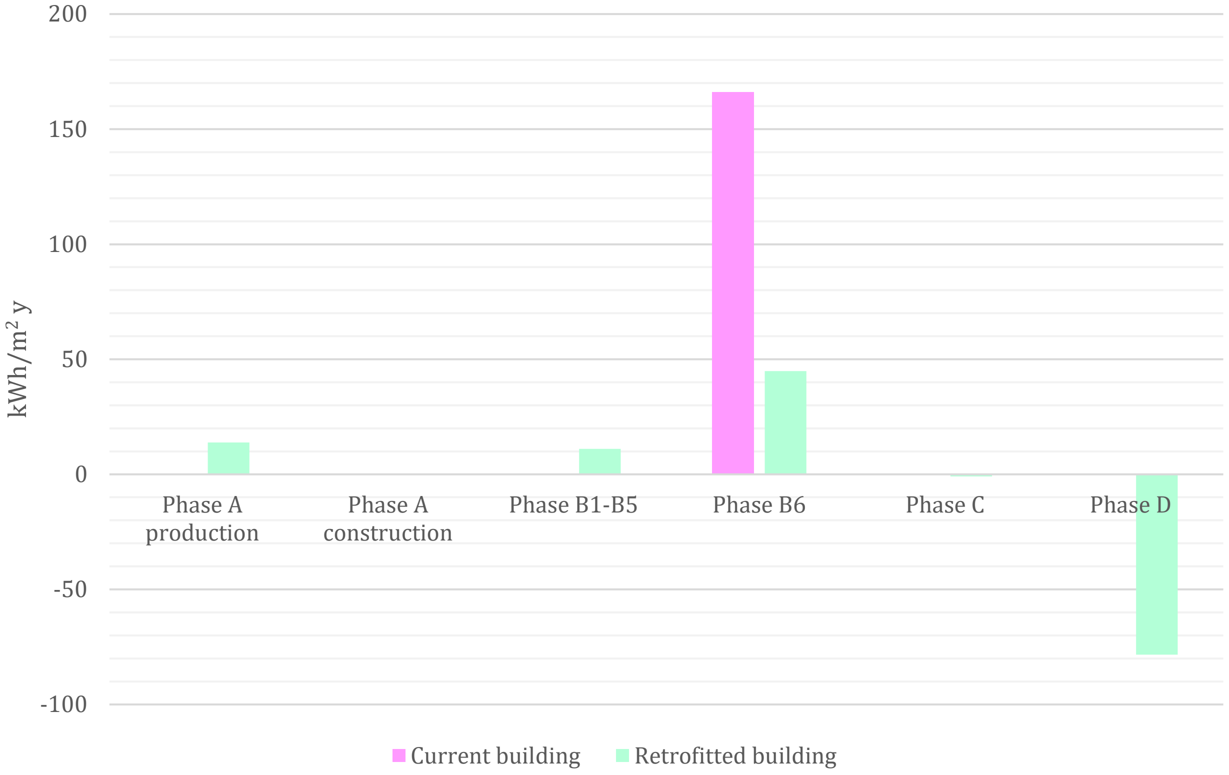


Figure 48. *Cumulative energy demand of the building before and after the retrofit. Only building-related energy demand is included.*

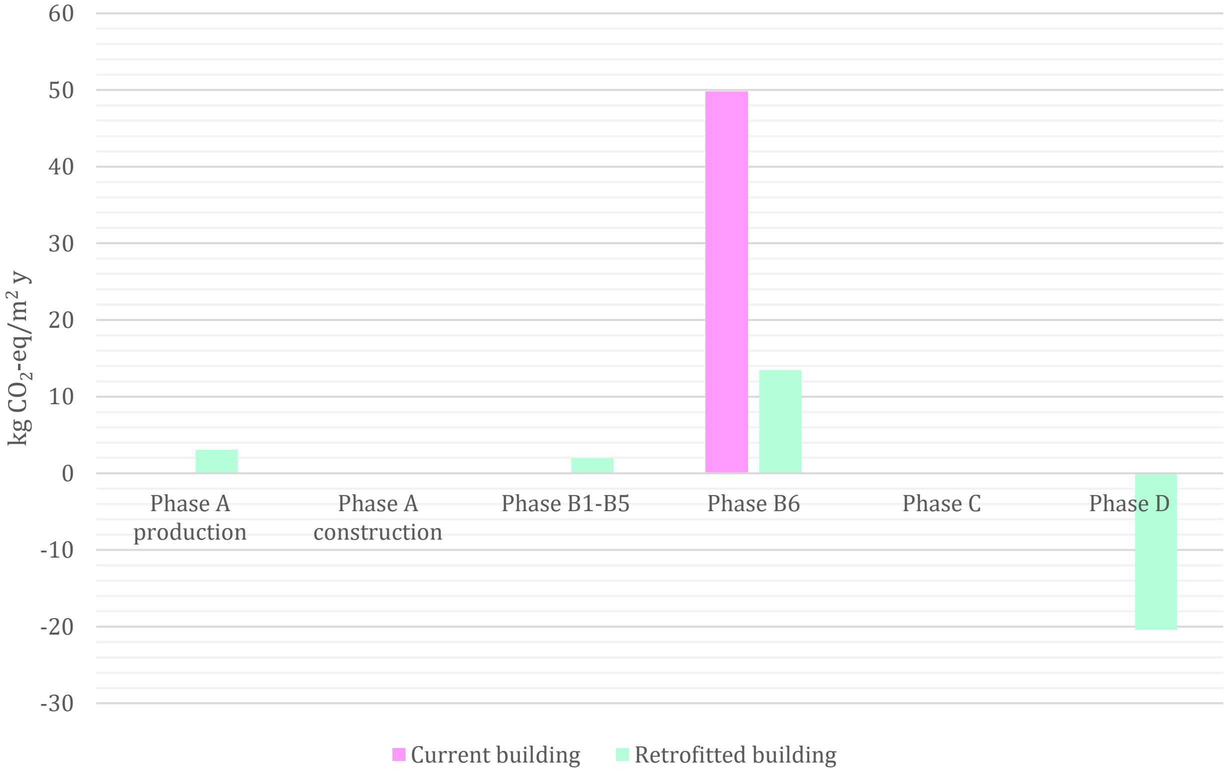


Figure 49. *Global warming potential of the building before and after the retrofit. Only building-related energy demand is included.*

LCA scenarios assessment

The cumulative energy demand was compared with the energy demand of the building before retrofitting. This comparison will show if the retrofitting results in a total reduction in energy demand and CO_2 emissions.

The current average energy usage in the apartments is 1091 m^3 natural gas and 1684 kWh electricity per year, based on meter data from Bo-Ex. The gas usage is assumed to cover the main part of the building-related energy demand. The households use gas for cooking as well, which is accounted for by a 3% correction and electricity for ventilation, but this is disregarded.

Figure 48 shows the current building-related energy demand, compared with the cumulative energy demand after retrofitting. The operational energy demand (B6 phase) is reduced by 73% due to the insulation and the efficiency of the heat pump. And in the retrofitted situation, this energy is compensated by the electricity generated by the solar panels. The energy required for the retrofit and maintenance is lower if compared with the operational energy. In total this results in a 106% reduction in cumulative energy demand.

Figure 49 shows the global warming potential in both situations. The trend is similar to the cumulative energy demand.

LCC results

The total costs of Utrecht demo project are 3868 euro per square metre (including VAT). **Figure 50** shows the costs per life cycle phase, whereas **Figure 51** shows the relative contribution of the life cycle phases. Phases A1-A5 + B5 make up nearly half of the total costs. This contrasts with the cumulative energy demand and global warming potential, where the operational energy makes up the largest part.

LCC scenarios assessment

The life cycle costs were compared with the local practice. The total cost of the local practice is 4077 euro per square metre (including VAT). Utrecht demo project has a cost reduction of 4% compared to the local practice.

Figure 52 shows the LCC of local practice if compared with our demo case. The local practice has a lower initial investment, as is to be expected given the smaller amount of work to be done. However, the second renovation in 2035 to become natural-gas free and the highest energy bills compensate for this initial lower investment, resulting in an overall cost reduction for the selected retrofit approach.

Figure 53 shows the relative share of the contribution of each life cycle share to the total costs for the reference scenario. The large share in the total costs in the maintenance phase, i.e. the second renovation and the energy costs are apparent.

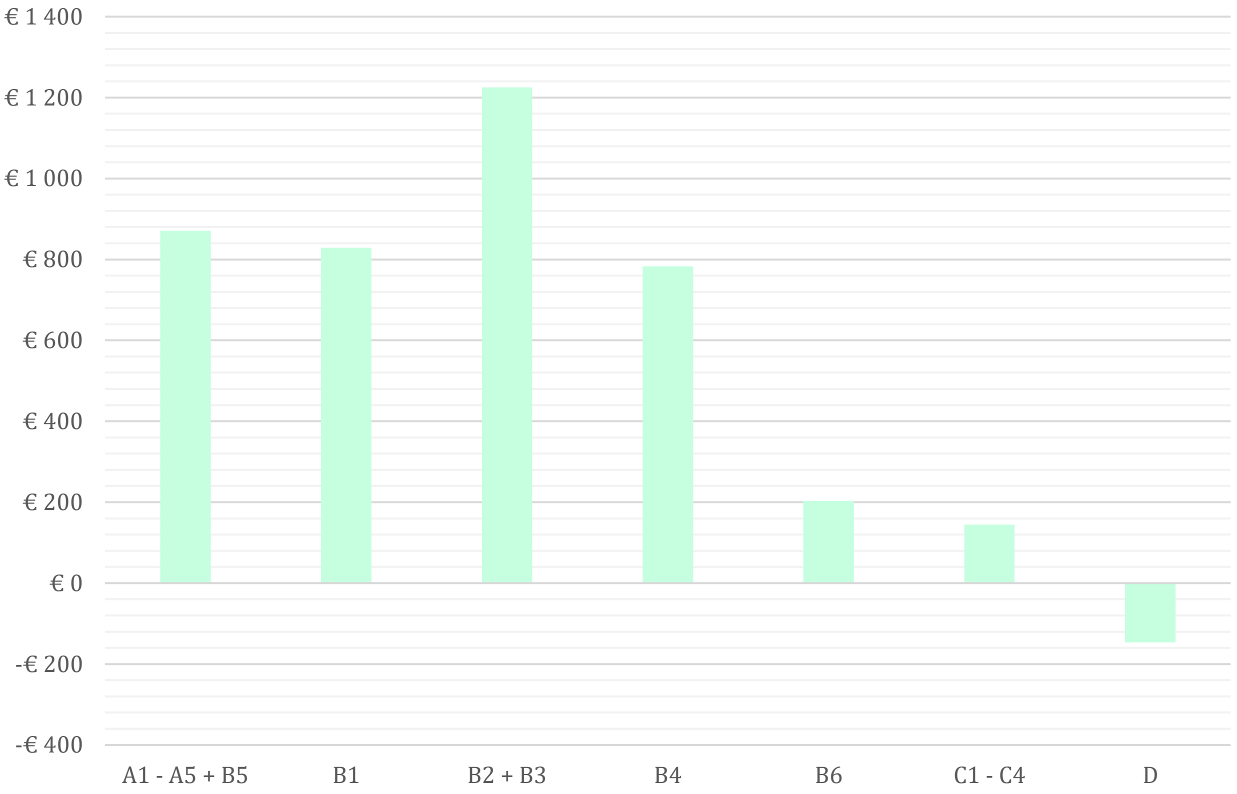


Figure 50. *Life cycle costs in the Utrecht demo case.*

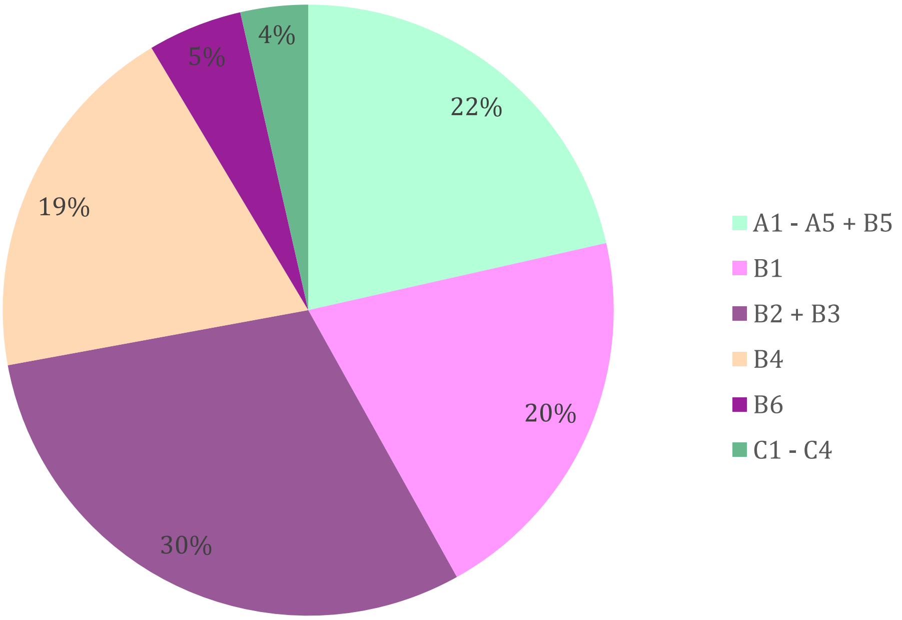


Figure 51. *Share of the different life cycle stages in the total life cycle costs of the retrofit in Utrecht (module D is excluded). Only the building-related energy is included in the figure.*

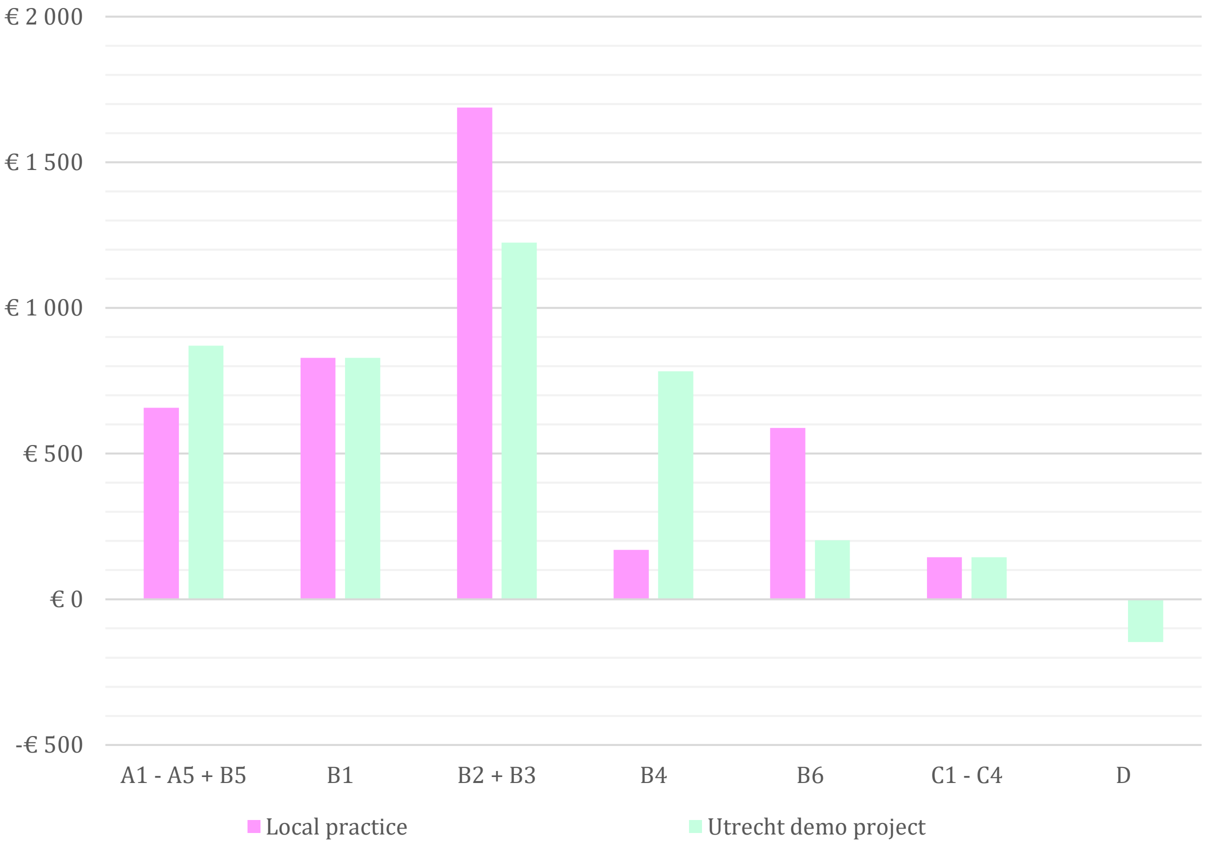


Figure 52. Life cycle costs in the Utrecht demo case compared to local practice.

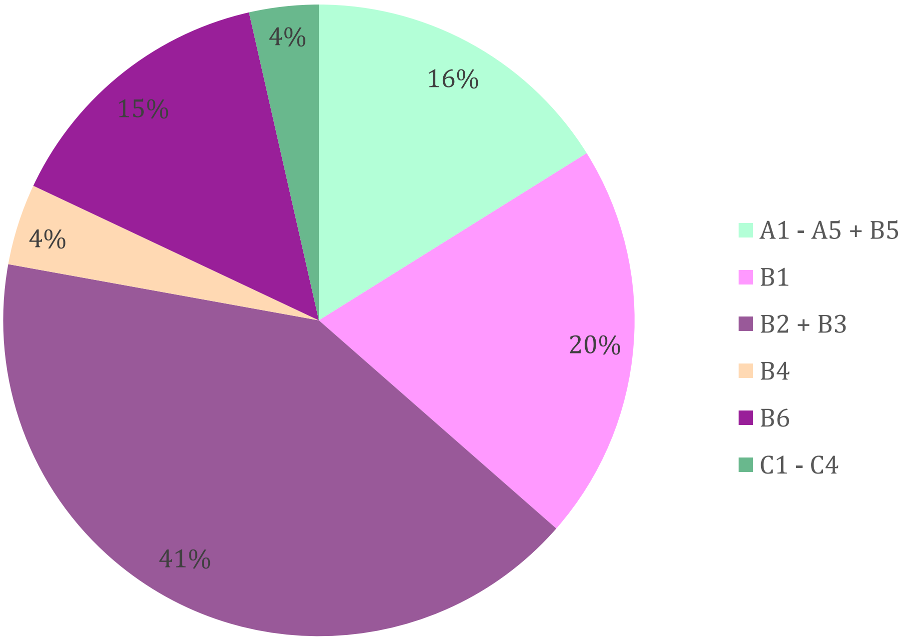


Figure 53. Breakdown of the different life cycle stages in the total life cycle costs of the local practice reference scenario in Utrecht. Only the building-related energy is included in the figure.

CONCLUSIONS AND FUTURE UPDATES

This report addressed the strategies implemented during the design phase by some of the ARV demonstration projects to reduce the life cycle environmental impacts of the construction sector. The focus was concentrated on the impacts related to climate change and into the use of energy resources, fossil and non.

All case studies implemented a quite similar approach, which translates in the definition of NZEB provided by each EU country:

- Reduction of the operational energy consumptions of the building through the high insulation of the envelope, the correction of thermal bridges, the increase of the envelope air tightness and the control of solar gains from transparent surfaces.
- Introduction of highly efficient energy generation systems such as condensing boiler or heat pumps.
- Integration of renewable energy generation systems

In relation to the first point, very ambitious limits about the thermal performance and the air tightness of the envelope are established in the countries where the demos are located.

The highly efficient generation systems considered include condensing gas boilers, district heating networks, and heat pumps. Here the selection mainly depends on the temperature desired: when heat at a high temperature (70-90°C) is needed, condensing boilers or district heating are selected; instead, when **low temperature** heat can be exploited (e.g., though the installation of radiant underfloor systems or air systems) heat pumps were considered. It is important to underline that **electrification** can also represent a strategy to increase the self-consumption of the photovoltaic energy produced in loco since all the demonstration projects highly rely on this technology.

The integration of renewable energy systems, in fact, consists mainly in the installation of PV systems. A huge integration even in the façades with a non optimal orientation is pursued to maximize the positive energy balance between the energy delivered to the building and injected into the national electricity grids. The benefits achievable are consistent in the life cycle of the building, linked to the increase of the self-consumption of the building but, first of all, to the possibility of substituting energy from fossil resources at a broader scale.

All demos reported **environmental benefits** in the life cycle of the implemented ARV interventions when compared with the local practice. In particular, considering the renovations:

- Karvina showed a very significant reduction of the operational energy consumption and GHG emissions for heating and DHW after the renovation (-62%); however, when the contribution of the embodied impacts is considered through the application of the proposed streamlined LCA methodology, the benefits are reduced to about 45% when excluding the PV system and to 58% when including it.
- Oslo found carbon payback times between 32 and 51 years for the H-building renovation depending on the emission intensity considered in the assessment (Norwegian or EU28).
- Trento reported a 73% saving in relation to the operational non-renewable energy requirement of the building and a 77% reduction in the relation to the operational GHG emissions. This outcome is linked to the low energy performance of the baseline non-renovated building. When considering the life cycle and excluding the renewable energy generation systems, the contribution of embodied impacts emerged, and the savings were respectively reduced to 70% and 72%. If the benefits achievable through the renewable electricity production are accounted, further savings can be achieved (e.g., -87% in relation to the life cycle GWP of the apartment building).
- Utrecht showed a reduction of 73% in relation to the operational CED and an overall reduction of 103% in the life cycle, which is directly linked to the renewable energy produced.

Looking at the new constructions, both Palma and Trento concurred that converting the NZEB design into a PEB ambition through the installation of additional PV capacity could yield additional environmental benefits. As an example, Palma documented a six-month payback period, which served to offset the increased embodied emissions associated with installing additional 36 PV panels (52 were initially planned for the NZEB concept and then 88 for the PEB one). This balancing act was achieved through the emissions savings attributed to renewable energy generation. Moreover, Oslo determined a payback period ranging from 12 to 18 years for the upgrading of the reference design scenario (in accordance with Norwegian legislation requirements) to a PEB.

These outcomes should be considered critically because they are linked to the energy performance of the baseline and to the simplified calculation methodologies implemented for the calculation of the energy savings and PV exchange with the grids.

Cost benefits are harder to achieve. Below are the main results obtained.

- For the renovated building in Palma, the implementation of the passive and active energy efficiency measures leads to a 64% reduction in the global costs in 50 years compared with the current stage of the building, while giving a significant reduction in the energy costs (around 95%).
- Considering the renovation in Povo, instead, no cost benefits are realized in the life cycle of the intervention unless incentives are taken into account.
- No cost benefits are expected in Oslo under the current energy prices and construction costs.
- Utrecht reported a life cycle cost reduction of 5% compared to the local practice, which is lower than the ARV ambition.

A significant **burden shifting** on embodied components was experienced by all demos, a factor that worked to limit the life cycle savings in comparison with the operational ones alone. LCA/LCC applications were useful instruments that allowed to assess their contribution to the life cycle of the interventions: embodied GWP arrived at accounting for 30% in Karvina, 16% in Trento, 11% in Palma, and 36% in Utrecht renovations. A higher incidence was experienced for new constructions (e.g., up to 54% in Trento and 47% in Palma).

The **reuse of existing materials** in energy renovations was the most effective strategy implemented to contain the trade-off on embodied environmental burdens experienced for new constructions. All the demos decided to adopt a burden free approach to maximize the benefits achievable through this strategy. The lower embodied GWP in **renovations in comparison with new constructions** (3.39-5.30 kg CO_2e/m^2y against 9.69-12.29 kg CO_2e/m^2y, see **Table 44**) is caused by the neglection of the impacts inherited from reused materials.

The future updates for this activity foresee the verification of the expected performances displayed in this report through real monitored data.

Table 44. *LCA benchmarks and results.*

Demo project	**Embodied+EoL GWP kg CO_2e/m^2 y**	**GWP (B6) kg CO_2e/m^2 y**	**GWP (life cycle, no PV) kg CO_2e/m^2 y**	**GWP (life cycle + PV) kg CO_2e/m^2 y**
Trento ex-Zuffo (new nZEB)	9.69	7.31	17.00	7.91
Trento ex-Zuffo (new PEB)	12.29	7.31	19.60	2.00
Palma (new building)	11.97	6.09	18.06	Benefits from the renewable energy export in stage D are planned to be calculated in the later stage of the project.
Palma (renovated building)	5.30	8.29	13.59	
Povo (Trento)	4.46	19.54	24.00	11.30
Utrecht	5.05	13.45	18.50	-1.94
Karvina	3.39	6.94	10.33	7.62

REFERENCES

Asdrubali, F., Baggio, P., Prada, A., Grazieschi, G., Guattari, C., 2020. Dynamic life cycle assessment modelling of a NZEB building. Energy 191, 116489. https://doi.org/10.1016/j.energy.2019.116489

Asdrubali, F., Baldassarri, C., Fthenakis, V., 2013. Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. Energy and Buildings 64, 73–89. https://doi.org/10.1016/j.enbuild.2013.04.018

Asdrubali, F., Desideri, U. (Eds.), 2019. Handbook of Energy Efficiency in Buildings. Elsevier. https://doi.org/10.1016/C2016-0-02638-4

Asdrubali, F., Grazieschi, G., Roncone, M., Thiebat, F., Carbonaro, C., 2023. Sustainability of Building Materials: Embodied Energy and Embodied Carbon of Masonry. Energies 16, 1846. https://doi.org/10.3390/en16041846

Cabeza, L.F., Boquera, L., Chàfer, M., Vérez, D., 2021. Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. Energy and Buildings 231, 110612. https://doi.org/10.1016/j.enbuild.2020.110612

Casarin, T., 2021. Examining the effect of government incentives on energy efficiency retrofitting in the Italian real estate market. Ca' Foscari University of Venice, Venice.

CEN, 2012. EN 15804 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. Brussels, Belgium.

Chau, C.K., Yik, F.W.H., Hui, W.K., Liu, H.C., Yu, H.K., 2007. Environmental impacts of building materials and building services components for commercial buildings in Hong Kong. Journal of Cleaner Production 15, 1840–1851. https://doi.org/10.1016/j.jclepro.2006.10.004

Crawford, R., 2020. Life Cycle Assessment in the Built Environment. ROUTLEDGE, S.l.

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. Building and Environment 54, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005

CYPE Ingenieros, 2018. BREEAM® España valida el software de CYPE que calcula el impacto ambiental generado en la edificación [WWW Document]. URL https://info.cype.com/es/noticias/breeam-espana-valida-el-software-de-cype-que-calcula-el-impacto-ambiental-generado-en-la-edificacion/

De Masi, R.F., Festa, V., Gigante, A., Parrotta, M., Ruggiero, S., Russo, A., 2023. Sensitivity analysis about the effectiveness of the energy efficiency measures for residential building under the Italian incentive opportunities, in: 2023 8th International Conference on Smart and Sustainable Technologies (SpliTech). Presented at the 2023 8th International Conference on Smart and Sustainable Technologies (SpliTech), IEEE, Split/Bol, Croatia, pp. 1–4. https://doi.org/10.23919/SpliTech58164.2023.10193556

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L., 2020. Review of 50 years of EU energy efficiency policies for buildings. Energy and Buildings 225, 110322. https://doi.org/10.1016/j.enbuild.2020.110322

Efinovatic, 2023. CE3Xv2.3 [WWW Document]. URL http://www.efinova.es/CE3X

European Commission, 2012. 2012/c 115/01. Official Journal of the European Union C115, 55. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2012:115:FULL:EN:PDF

Finnegan, S., Jones, C., Sharples, S., 2018. The embodied CO2e of sustainable energy technologies used in buildings: A review article. Energy and Buildings 181, 50–61. https://doi.org/10.1016/j.enbuild.2018.09.037

Foraboschi, P., Mercanzin, M., Trabucco, D., 2014. Sustainable structural design of tall buildings based on embodied energy. Energy and Buildings 68, 254–269. https://doi.org/10.1016/j.enbuild.2013.09.003

Government of Spain, 2019. Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314/2006, de 17 de marzo. [WWW Document]. URL https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-18528 (accessed 10.1.24).

Government of Spain, 2016. Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España.

Grazieschi, G., Asdrubali, F., Thomas, G., 2021. Embodied energy and carbon of building insulating materials: A critical review. Cleaner Environmental Systems 2, 100032. https://doi.org/10.1016/j.cesys.2021.100032

Kjær Zimmermann, R., Nygaard Rasmussen, F., Kanafani, K., Malabi Eberhardt, L.C., Birgisdóttir, H., 2022. Reviewing allocation approaches and modelling in LCA for building refurbishment. IOP Conf. Ser.: Earth Environ. Sci. 1078, 012095. https://doi.org/10.1088/1755-1315/1078/1/012095

Liang, Y., Li, C., Liu, Z., Wang, X., Zeng, F., Yuan, X., Pan, Y., 2023. Decarbonization potentials of the embodied energy use and operational process in buildings: A review from the life-cycle perspective. Heliyon 9, e20190. https://doi.org/10.1016/j.heliyon.2023.e20190

Machairas, V., Tsangrassoulis, A., Axarli, K., 2014. Algorithms for optimization of building design: A review. Renewable and Sustainable Energy Reviews 31, 101–112. https://doi.org/10.1016/j.rser.2013.11.036

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2020. NTA 8800:2020+A1:2020: Energieprestatie van gebouwen [WWW Document]. URL https://rijksoverheid.bouwbesluit.com/Inhoud/docs/norm/nta8800-2020 (accessed 12.15.23).

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019. Besluit van 13 december 2019, houdende wijziging van het bouwbesluit 2012 en van enkele andere besluiten inzake bijna energie-neutrale nieuwbouw [WWW Document]. URL https://zoek.officielebekendmakingen.nl/stb-2019-501.html (accessed 12.15.23).

Obrecht, T.P., Jordan, S., Legat, A., Ruschi Mendes Saade, M., Passer, A., 2021. An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment. Journal of Cleaner Production 327, 129527. https://doi.org/10.1016/j.jclepro.2021.129527

Ortiz, O., Bonnet, C., Bruno, J.C., Castells, F., 2009. Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain. Building and Environment 44, 584–594. https://doi.org/10.1016/j.buildenv.2008.05.004

Planbureau voor de Leefomgeving, 2021. Klimaat- en energieverkenning 2021 [WWW Document]. URL https://www.pbl.nl/uploads/default/downloads/pbl-2021-klimaat-en-energieverkenning-2021-4681.pdf (accessed 12.15.23).

Pomponi, F., De Wolf, C., Moncaster, A. (Eds.), 2018. Embodied Carbon in Buildings: Measurement, Management, and Mitigation. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-72796-7

Potrč Obrecht, T., Jordan, S., Legat, A., Passer, A., 2021. The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures. Int J Life Cycle Assess 26, 839–851. https://doi.org/10.1007/s11367-021-01920-2

Preciado-Pérez, O.A., Fotios, S., 2017. Comprehensive cost-benefit analysis of energy efficiency in social housing. Case study: Northwest Mexico. Energy and Buildings 152, 279–289. https://doi.org/10.1016/j.enbuild.2017.07.014

Rabani, M., Madessa, H.B., Ljungström, M., Aamodt, L., Løvvold, S., Nord, N., 2021. Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building. Building and Environment 204, 108159. https://doi.org/10.1016/j.buildenv.2021.108159

Rijksdienst voor Ondernemend Nederland, 2023a. Energieprestatie - BENG [WWW Document]. URL https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/beng (accessed 12.15.23).

Rijksdienst voor Ondernemend Nederland, 2023b. Tabellen maximale energieprestatievergoeding [WWW Document]. URL https://www.rvo.nl/onderwerpen/energieprestatievergoeding-epv/tabellen-maximale (accessed 12.15.23).

Rijksdienst voor Ondernemend Nederland, 2023c. Standaard en streefwaarden voor woningisolatie [WWW Document]. URL https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/standaard-streefwaarden-woningisolatie (accessed 12.15.23).

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy 258, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings 35, 1049–1064. https://doi.org/10.1016/S0378-7788(03)00066-5

Stichting Bouwkwaliteit, 2019. Bepalingsmethode milieuprestatie gebouwen en GWW-werken [WWW Document]. URL https://milieudatabase.nl/ (accessed 1.15.24).

Victoria, M., Perera, S., 2018. Carbon and Cost Hotspots: An Embodied Carbon Management Approach During Early Stages of Design, in: Pomponi, F., De Wolf, C., Moncaster, A. (Eds.), Embodied Carbon in Buildings. Springer International Publishing, Cham, pp. 247–262. https://doi.org/10.1007/978-3-319-72796-7_11

Wiik, M.K., Fufa, S.M., Kristjansdottir, T., Andresen, I., 2018. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. Energy and Buildings 165, 25–34. https://doi.org/10.1016/j.enbuild.2018.01.025

ACKNOWLEDGEMENTS AND DISCLAIMER

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101036723.

APPENDIX A – GLOSSARY OF TERMS

Table A.1 *Abbreviations used in the report.*

Abbreviation	**Description**
BCR	Benefit-cost ratio
CPCC	Climate Positive Circular Communities
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
FU	Functional Unit
LCA	Life cycle Assessment
LCC	Life Cycle Cost
LCI	Life cycle Inventory
NPV	Net Present Value
NZEB	Nearly Zero Energy Building
PCR	Product Category Rules
PEB	Positive Energy Building
PV	Photovoltaic

PARTNER LOGOS

NTNU

Architects' Council of Europe
Conseil des Architectes d'Europe
ace-cae.eu

ČVUT
UCEEB

DTU

Danfoss
ENGINEERING TOMORROW

ENFOR

ProjectZero
SONDERBORG

eurac research

SINTEF

Ajuntament de Palma

IBAVI
Institut Balear de l'Habitatge
Govern de les Illes Balears

IREC
Shaping Energy for a Sustainable Future

metrovacesa

HU
UNIVERSITY OF APPLIED SCIENCES UTRECHT

HOUSING EUROPE

BURO DE HAAN

centerdenmark

S A B

Green Digital Finance Alliance

bo-ex | thuis in Utrecht

RCPANELS

Utrecht University

City of Utrecht

BOS
STERK IN DUURZAME OPLOSSINGEN

iwell

mex architects

woonin

KaRVINÁ

Dolomiti energia

habitech
IL DISTRETTO ENERGIA AMBIENTE

UNIVERSITÀ DI TRENTO

POLITECNICO DI TORINO

NANOPOWER

AIGUASOL

WWW.GREENDEAL-ARV.EU