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A Portfolio of Building Solutions Supporting Positive Energy District Transition: Assessing the Impact of Green Building Certifications

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Abstract: Positive Energy Districts (PEDs) represent an innovative approach to thinking and designing cities sustainably, in compliance with the European Union energy strategy. This strategy integrates sectors such as urban planning, energy, and construction to synergistically address energy and environmental challenges. Studies on sustainability assessment systems applied in PEDs evidenced that they focus mostly on energy aspects, while few include a comprehensive life cycle assessment of equivalent CO_2 emissions, considering the building component and the impacts of the materials used. Additionally, most assessments are conducted on the urban and district scale, such as Neighborhood Sustainability Assessments (NSA), which begin to correlate PEDs with the dynamics of selecting sustainable materials for green-certified projects, analyzed throughout the entire life cycle, relying on the adoption of Green Building Rating Systems (GBRS) at the building scale. To explore the impact of environmentally friendly (i.e., 'green') GBRS certifications in the selection of building materials and products according to sustainability criteria, and to encourage their use in projects explicitly referring to PEDs, this study analyzes the technical solutions implemented in two significant residential building renovation projects in Italy from a PED perspective. It proposes a classification system based on the required targets of energy efficiency, energy production, and energy flexibility. The results include the definition of an expandable portfolio of technical solutions, an analytical comparison between the materials used in the energy renovation projects of the case studies examined, and the sustainability criteria provided by voluntary 'green' certification tools (GBRS). The collected evidence offers an operational framework that confirms the positive impact of GBRS certifications and the related selection of materials on sustainable urban development, contributing to the scientific debate on PEDs. Furthermore, the use of voluntary 'green' certifications at the building scale can be encouraged in the context of the transition towards PEDs, aiming to identify specific criteria and indicators for the selection of building materials to be integrated into future PED certifications. This aims to contribute to creating energy self-sufficient urban areas, focusing on sustainability, efficiency, and innovation, in line with global emission reduction and climate change mitigation goals.

Keywords: Positive Energy District; green building rating systems; technical solutions; building materials and products

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1. Introduction

In the context of global urbanization, cities play a pivotal role in energy consumption and climate change, accounting for a substantial portion of global CO_2 emissions. However, they also drive economic development, contributing significantly to global Gross Domestic Product (GDP).

Global initiatives such as the 2030 Agenda, New Urban Agenda, and Paris Agreement outline strategies for sustainable urban development. In Europe, the "2020 Climate and Energy Package" and "2030 Climate & Energy Framework" provide guidance for climate action. The EU's long-term strategy aims for a climate-neutral EU by 2050, emphasizing district-level approaches such as Positive Energy Districts (PEDs).

According to the White Paper on the PED Reference Framework, "PEDs are urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users, and the regional energy, mobility, and ICT systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainability" [1].

Thus, the transition to PEDs is a crucial goal to address global challenges such as climate change, environmental sustainability, and energy security.

Positive energy balance in PEDs must be guaranteed through the simultaneous achievement of three main "goals": energy efficiency, local energy production, and energy flexibility [1]. This paradigm, promoted by European initiatives such as the European Green Deal [2] and the Renovation Wave Strategy [3], which provide essential regulatory frameworks to support PEDs [4], involves a profound transformation of the built environment. This transformation encompasses the design of new buildings and, even more significantly, the renovation of existing ones.

The Renovation Wave Strategy, in particular, aims to double the rate of energy renovations to improve the energy performance of buildings, placing the principle of "Efficiency First" at the forefront. This principle prioritizes energy-saving measures over increasing energy production.

Within the PED transition, the concept of a "positive energy balance" must therefore be considered broadly, aiming for net zero greenhouse gas (GHG) emissions by including the sustainable use of construction materials in energy assessments [5].

The construction industry is one of the most impactful sectors in terms of energy emission and raw material consumption [6]. Therefore, improving the energy performance of buildings must be integrated with a sustainability-oriented and circular economy approach, favoring low-impact materials and conducting a comprehensive assessment of their life cycle (Life Cycle Assessment, LCA) to ensure the environmental balance of building renovations within PEDs.

Indeed, the new Energy Performance of Buildings Directive also introduces carbon footprint assessments based on LCA, to be included in Renovation Passports for existing buildings [7].

The consideration of the environmental impact of construction materials in building construction or renovation projects, and the subsequent need for an LCA methodology to support their selection during the early design stages, is a well-established topic in scientific research [8,9]. This issue is addressed not only at the building level but also on a broader scale, such as neighborhoods [10,11].

The selection of sustainable materials is a complex process that requires considering various parameters throughout the building's life cycle to achieve green building certifi-

cation [12]. In this context, a building's energy efficiency must be enhanced by utilizing low-impact or renewable natural resources [13].

The maturity of material selection processes in new constructions or building renovations is also evident through the observation of major green building rating systems (GBRS). Most of these systems include the selection of low-impact materials as part of the sustainability criteria for the building life cycle.

1.1. Neighborhoods Sustainability Assessment Tools and Material Selection Criteria

Despite the absence of specific certification protocols for Positive Energy Districts (PEDs), existing urban sustainability assessment tools represent a valuable starting point for addressing sustainability challenges at the district level [14].

The ISO/TR 37121 [15] and a report produced within the PED-ID project [16] map numerous systems for assessing the sustainability of urban and district-level interventions, known as Neighborhood Sustainability Assessment (NSA) tools [17,18].

Many studies have focused on comparative analyses of these tools, identifying their strengths and areas for improvement [19–26].

Specifically in the context of PEDs, Volpatti et al. [14] analyzed protocols such as LEED for Neighborhood Development (LEED-ND) [27], BREEAM Communities [28], and CASBEE for Cities [29], proposing the integration of additional criteria tailored to PEDs. These include surplus energy management, innovative business models for energy communities, and the evaluation of nature-based solutions.

Haase & Baer [30] examined two sustainability frameworks for PEDs, namely the "2000 W Site (2000 WS)" proposed in Switzerland and the "Zero Emission Neighborhood (ZEN) concept" developed in Norway. They related these frameworks to the concept of planetary boundaries, highlighting the environmental limits that must not be exceeded to prevent irreversible global changes. The same study underscored the importance of key performance indicators (KPIs) related to construction materials, including total greenhouse gas (GHG) emissions, lifecycle emission neutrality, and the adoption of sustainable materials based on circular economy principles, evaluated through Environmental Product Declarations (EPDs). These indicators are critical for adhering to planetary boundaries associated with climate change and land use.

Guarino et al. [31] discussed the state of the art in sustainability assessments for PEDs, emphasizing environmental, social, and economic applications. Among the key environmental KPIs, the study highlighted direct emissions, lifecycle indicators (LCA), and those linked to circular economy strategies. It also pointed out that the range of lifecycle indicators should encompass air pollution generated along the material supply chain.

The literature highlights a frequently overlooked issue: the accounting of indirect carbon emissions, which is often limited to the operational phase in the definition and assessment of PEDs [31]. This omission risks producing carbon balances that are far from realistic, undermining the achievement of true carbon neutrality. The embodied energy of construction materials is a critical factor that demands greater attention when evaluating the energy performance of buildings and districts to achieve effective urban decarbonization [32].

A more specific evaluation of material selection criteria in NSA tools was conducted by Yoon & Park [19], who examined BREEAM Communities [28], LEED-ND [27], and CASBEE-UD [33], along with four urban design guidelines. They structured a framework for material sustainability indicators based on the three pillars of sustainability—social, environmental, and economic—and categorized them by application domains such as landscape, infrastructure, and buildings.

For this article, focusing on the "buildings" domain, a review of indicators related to material selection at the urban scale was conducted, as summarized in Table 1.

Table 1. Indicators related to material selection at district scale.

NSA	Category	Criteria	Requirements
LEED v4 for Neighborhood Development (2018)	Green infrastructure and buildings	Certified Green Buildings	Design, build, or retrofit at least one building in the project or a portion of the total floor area to meet LEED certification or a similar green building rating system reviewed by an independent third-party accredited to ISO standards
		Recycled and Reused Infrastructure	Ensure that at least 50% of the total mass of infrastructure materials comes from a combination of post-consumer recycled content, on-site reused materials, and half of the pre-consumer recycled content. This applies to roadways, parking lots, sidewalks, curbs, water retention tanks, base materials, and utility piping (e.g., rainwater, sewer, or energy distribution). Recycled content must meet the ISO/IEC 14021 [34] standards for environmental claims
BREEAM Communities (2012)	Resources and energy	Sustainable buildings	The developer and design team committed to designing new or renovated buildings on-site to meet industry best practices in sustainability, focusing on energy, water, waste, material impacts, and occupant health and well-being
		Low impact materials	Contractors and sub-contractors must have environmental management systems, like EMAS [35] or ISO14001 [36], to ensure sustainable material management in the public realm [1]. Credits are awarded based on the percentage of materials used that achieve an A+ to B rating in the Green Guide to Specification
CASBEE-UD (2014)	Resources recycling—Construction	Wood Material	Utilization level of wood materials produced from sustainable forests
		Recycled Material	Average usage of certified recycled items in a building in the block

[1] This issue does not cover the use of materials in the buildings themselves.

This review revealed that the observed NSA tools primarily focus on reducing the environmental impact of materials in public space design, while the proper selection of materials at the building scale is often left to the presence of green-certified buildings.

1.2. Green Building Rating Systems and Material Selection Criteria

At the building scale, Green Building Rating Systems (GBRS), including Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), represent the most established frameworks for evaluating and certifying the ecological and environmental performance of buildings [37,38]. These protocols also include specific criteria for material selection based on sustainability principles.

Since 2008, European policies, through the adoption of Green Public Procurement (GPP) [39], have stressed the importance of integrating environmental criteria into public

procurement processes. Some national legislations have made GPP criteria mandatory. In Italy, for instance, the legislator adopted the Minimum Environmental Criteria (CAM) for 18 product categories, including construction, to achieve strategic objectives such as resource efficiency and conservation, waste reduction, and the minimization of hazardous substance emissions [40].

The same decree [40] recognizes the importance of GBRS as tools to demonstrate compliance with established environmental requirements. Specifically, the decree lists both national and international energy and environmental sustainability protocols, including LEED [41], BREEAM [42,43], and KlimaHaus Nature [44]. This approach allows designers to streamline the verification process, using certifications as evidence of compliance. However, it is essential that the documentation demonstrates adherence to all relevant environmental requirements, ensuring alignment between GBRS and the standards mandated by CAM.

In the literature, numerous studies compare different GBRS [8,45–49]. For instance, Park et al. [8] examine how various systems evaluate material-related aspects, while Braulio-Gonzalo et al. [50] analyze the coverage of the three dimensions of sustainability (environmental, social, and economic) and their relationship with the life cycle stages proposed by the EN 15978 standard [51].

A more detailed analysis of LCA methodologies within GBRS was conducted by Izaola et al. [52], which evaluate how five major European schemes integrate LCA into their certification processes. The study highlights significant differences in the adopted methodologies, undermining the comparability of results, and emphasizes challenges such as the lack of standardized data, the complexity of LCA calculations, and the need for specialized training.

To address these issues and provide a unified methodology at the European level, the Level(s) framework, promoted by the European Commission, offers a set of reference indicators to monitor and improve building sustainability throughout their entire life cycle [53].

A review of potential criteria and indicators for material selection at the building scale is summarized in Table 2.

This review highlights several recurring selection criteria. These include reducing greenhouse gas emissions by calculating global warming potential (GWP) and other LCA parameters; prioritizing (or mandating) the use of third-party-certified materials that adhere to environmental standards for sustainable sourcing and production; minimizing emissions related to transportation from production sites to construction sites; using reclaimed, recycled, or recyclable and durable materials; and excluding highly polluting or toxic materials, non-recyclable materials, and those that fail to comply with waste management regulations.

However, despite the widely recognized importance of selecting eco-compatible products and verifying their environmental impact through EPDs based on LCA principles, most evaluation tools, particularly in the context of PEDs, predominantly focus on energy-related aspects. Only 7% conduct a full life cycle assessment of CO_2-equivalent emissions [57].

While GBRS are widely acknowledged as valuable by the market and numerous models and tools are available, their application at the district level remains limited [58].

Table 2. Indicators related to material selection at the building scale.

Gbrs/Protocols	Category	Criteria/Indicator/Credit	Requirements
BREEAM Domestic Refurbishment (2014)	Materials	Environmental impact of materials	Assess the embodied impact and thermal performance of roofs, walls, windows, and floors using the Mat 01 calculator [1], based on the Green Guide rating of new materials and their contribution to thermal efficiency
		Responsible sourcing of materials	All new timber must be legally sourced and assessed with the Mat 02 calculator [1] based on responsible sourcing levels. Additional credits are available for having a sustainable procurement plan
		Insulation	New insulation in walls, floors, roofs, and building services must meet minimum assessment requirements
BREEAM International Non-Domestic Refurbishment (2015)	Materials	Environmental impact of materials	Reduce the building's life cycle environmental impacts by reusing materials and analyzing the impact of new materials using reliable life cycle assessment tools for the mail-building elements
		Responsible sourcing of materials	Materials are sourced according to a sustainable procurement plan, ensuring key building materials are responsibly sourced to minimize environmental and socio-economic impacts
		Designing for durability and resilience	The building incorporates measures to reduce damage as well as wear and tear, with design and materials specified to limit degradation caused by environmental factors
		Material efficiency	Measures have been identified and implemented to optimize material use
LEED v4.1 RESIDENTIAL BD + C MULTIFAMILY HOMES (2020)	Materials and Resources	Building Life-Cycle Impact Reduction	Demonstrate reduced environmental effects during initial project decision-making by reusing existing building resources or demonstrating a reduction in materials use through life-cycle assessment. Achieve one of the following options: Historic Building Reuse; Renovation of Abandoned or Blighted Building; Building and Material Reuse; Whole-building Life-Cycle Assessment
		Environmentally Preferable Products	At least 70% (by weight or volume) of each compliant building component must meet the following criteria: - Contain at least 25% reclaimed materials (e.g., salvaged, reused, refurbished materials, including wood by-products like secondary manufacturing items or recovered wood). - Contain at least 25% post-consumer or 50% pre-consumer recycled content. - Wood products must be FSC-certified or an equivalent approved standard. - Bio-based materials must meet the Sustainable Agriculture Standard, pass ASTM D6866 testing, and be legally harvested. Leather and other animal-based products are excluded. - Concrete must include at least 30% fly ash or slag as a cement substitute. - Products should come from manufacturers participating in extended producer responsibility programs
			Building product disclosure and optimization (BPDO)—Use materials with verified environmental impacts disclosed through EPDs BPDO—Sourcing of Raw Materials: ensure materials are responsibly sourced BPDO—Material Ingredients: select products with transparency in material ingredient disclosure
		Construction and Demolition Waste Management	- Recycle or salvage nonhazardous construction and demolition materials. Calculations must be consistent (by weight or volume): Exclude excavated soil and land-clearing debris from calculations. Count materials used as alternative daily cover (ADC) and wood waste converted to biofuel as waste, not as a diversion. Other waste-to-energy processes are not eligible for diversion credits. For international projects, waste-to-energy systems may count as a waste diversion if they comply with the European Commission Waste Framework Directive 2008/98/EC [54], Waste Incineration Directive 2000/76/EC [55], and CEN EN 303 standards [56] for waste-to-energy - Diversion of waste materials - Reduction in Total waste generated

Table 2. *Cont.*

Gbrs/Protocols	Category	Criteria/Indicator/Credit	Requirements
KlimaHaus Nature (2017)	Environmental Impact of Building Materials	Material/products-related Parameters	- Non-renewable primary energy (PEI nr) - Acidification potential (AP) - Greenhouse effect potential (GWP100) - Durability of materials (time of use) - Distance of the production site (place of raw material extraction, processing, and supply) from the construction site;
		Bonus	- Presence of an ecological certificate from a third party
		Data source	- KlimaHaus Material database [2] - EDP
		Prohibitions	- List of materials not allowed [3]
Level(s)	1: Greenhouse gas and air pollutant emissions along a building's life cycle	Indicator 1.2	Life cycle Global Warming Potential (GWP)
	2: Resource efficient and circular material life cycles	Indicator 2.1	Bill of Quantities, materials, and lifespans
		Indicator 2.2	Construction and Demolition Waste (CDW) and materials
CAM-Italy	Technical specifications for construction products	Thermal and acoustic insulation [4]	Thermal and acoustic insulation must meet the following criteria: - Have CE marking. - Contain no Substances of Very High Concern (SVHC) per REACH Regulation, exceeding 0.1% by weight. - Must not use ozone-depleting (ODP) blowing agents (e.g., HCFCs). - Must not be made with lead-based catalysts during spraying or foam formation. - Expandable polystyrene must have blowing agents below 6% of the product's weight. - Mineral wool must comply with Note Q or Note R of Regulation (EC) No. 1272/2008 (CLP). - For materials listed in the table [5], they must include the minimum required recycled, recovered, or by-product content by weight.

[1] Mat 01 calculator and Mat 02 calculator are tools used in the BREEAM Domestic Refurbishment assessment to assign credits based on the sustainability and environmental impact of materials. [2] KlimaHaus Material database provides specific data on a range of construction materials, with a particular focus on environmental parameters. [3] The protocol provides a list of materials prohibited or not allowed for certification purposes. [4] Other criteria, omitted here for the sake of brevity, pertain to the following categories: emissions in confined spaces (indoor pollution); on-site mixed and ready-mixed concrete; prefabricated products in concrete, autoclaved aerated concrete, and vibro-compressed concrete; steel; bricks and clay products; wood-based products; partition walls, perimeter cladding, and suspended ceilings; masonry in stone and mixed materials; flooring; PVC windows and shutters; PVC and polypropylene pipes; paints and coatings. [5] The table is provided within the decree.

1.3. Objectives and Structure of the Article

This article aims to examine the impact of green building certifications and their material selection criteria within the context of the transition to PEDs, using a case study analysis.

Previous studies have analyzed PED case studies by classifying the adopted solutions based on technological factors, local circumstances, and planning and implementation processes [59]. Other research has compared case studies, highlighting key success factors, including technological solutions, local constraints, and the roles of public or private entities in the realization of PEDs [60]. A collection of technical solutions and best practices for PEDs is also included in the PED implementation guidelines developed within the Making-City project [61].

However, none of these studies have classified technical solutions based on the three distinctive PED targets: energy efficiency, renewable energy production, and energy flexibility. The main sustainability criteria found in GBRS, such as the use of materials with recycled content, the proximity of production sites to construction sites, and the presence of third-party ecological certifications, will be correlated with the technical solutions implemented to meet the three PED targets.

This study focuses on two main research questions:

1. What recurring technical solutions can support achieving the three PED targets (energy efficiency, renewable energy production, and energy flexibility), and which materials are most commonly used for these solutions?
2. To what extent do sustainability criteria influence the selection of materials used for these solutions?

The results of this research include the following:

1. The definition of a portfolio of technical solutions for the transition to PEDs, which can be implemented and updated over time;
2. A comparison between the materials used in energy efficiency interventions and the requirements established by the main GBRS.

Through this analysis, the article aims to make a significant contribution to the scientific debate on PEDs by offering an operational framework to align building renovation interventions with environmental certifications in the Italian context.

The paper is structured into four sections. In addition to this Introduction, Section 2 describes the research phases and analysis methods used to assess two PED case studies in Italy. Section 3 highlights the results of the case study analysis. Finally, Section 4 presents the conclusions in relation to the research questions and the outlined objectives, discussing the limitations and potential future developments of the study.

2. Materials and Methods

To conduct a survey of relevant PED projects in Italy, the PED Booklet [62] and the "PED Database" from COST ACTION PED-EU-NET [63] were consulted. A total of ten projects were identified within the municipalities of Bassano del Grappa, Bologna, Bolzano, Florence, Lecce, Milan, Parma, Rome, and Trento.

From this initial selection, specific projects were chosen based on criteria such as the type of building renovation interventions aimed at improving energy efficiency, the accuracy and completeness of the available technical and procedural documentation, and the essential condition that the interventions were effectively implemented.

In particular, the study focused on two projects that met the aforementioned selection criteria: the REPLICATE project in Florence (initiated in 2016 and completed in 2021) and the SINFONIA project in Bolzano (initiated in 2014 and completed in 2020) [64]. Both projects were outcomes of Horizon2020 PED initiatives.

These projects included interventions on a series of buildings identified based on their location (Table 3).

Table 3. The case studies within the two selected PED projects in Italy.

Florence-REPLICATE		Bolzano-SINFONIA	
Via Marche 3-5-11	Building 1 *	Via Palermo 74-76-78-80	Building 2 *
Via Liguria 6-10-14		Via Brescia 1-3-5; Via Cagliari 10-10/A	Building 3 *
Via Nave di Barozzi alle Piagge 13/1-4		Via Passeggiata dei Castani	
Viale Guidoni	New building	Via Similaun	
Via Torre Degli Agli	New building	Via Aslago	
Via Toscanini	New building		
Viale Giannotti Ex Longinotti	New building		

* Building selected for the case study.

For both projects, an investigation was conducted into the technical solutions used for the renovation of three residential buildings.

The specific objectives of this investigation were as follows:

- to highlight the findings derived from the analysis of building renovation interventions;
- to identify the construction characteristics of recurring technical solutions;
- to verify whether specific measures for the selection of eco-sustainable construction products, considering their entire life cycle, were adopted in the observed projects.

Regarding the latter point, the analysis revealed that, in the case of REPLICATE, the procurement documents for the execution of works did not explicitly express any intention to adopt protocols to limit the environmental impact of materials.

In contrast, the SINFONIA project followed the KlimaHaus protocol, and as part of the project development, a dedicated certification for interventions on existing buildings, "KlimaHaus R", was also defined [65].

However, this certification does not consider the impact of construction materials. Therefore, the characteristics of the products used were assessed in accordance with the KlimaHaus Nature protocol, which includes a section on the "Environmental Impact of Construction Materials".

Consequently, for the analysis of the selected SINFONIA and REPLICATE projects, the research activities included the following:

- an in-depth study, conducted through a document review, of the residential building renovation interventions and their summarized graphical representation (see Sections 2.1 and 3.1);
- the identification of technical solutions and products used for their implementation (see Sections 2.2 and 3.2);
- the evaluation of the identified construction products concerning the environmental sustainability criteria present in green building certification protocols (see Sections 2.3 and 3.3).

2.1. Analysis of Building Renovation Projects

The transition to Positive Energy Districts (PEDs) in the selected cities involves a fundamental shift in urban paradigms, particularly in planning for energy-efficient building upgrades, starting with the renovation of public social housing. Within the context of the two Italian PED projects, an array of technical solutions was implemented to enhance the energy performance of the building stock, leading to CO_2 reductions, economic savings, and a significant contribution to sustainable urban development.

To this end, three social housing renovation projects were selected. For the REPLICATE project in Florence, the renovation of a residential building on Via Marche ("Building 1") in the Le Piagge neighborhood was chosen [66]. In the SINFONIA project in Bolzano, two cases were analyzed: the first on Via Palermo ("Building 2") [67] and the second on Via Brescia ("Building 3") [68].

For each of the three building renovation projects, a technical data sheet was developed using a framework proposed in a previous publication [69]. Each sheet included general information such as construction timelines, project financing, and objectives. Furthermore, the specific technical solutions implemented in each building to address the three PED targets—energy efficiency, energy flexibility, and energy production—were documented.

2.2. Analysis of Construction Technical Solutions

Following the collection of the general set of technical solutions, those related to the energy efficiency target were categorized into the following types:

- external wall insulation;
- roof/terrace insulation;
- external window replacement.

This categorization facilitated the development of a portfolio of solutions, offering an overview of various intervention alternatives and enabling effective comparisons.

For each solution, the associated construction products were identified and analyzed. Each product was examined based on its technical characteristics, including material composition, dimensions, supply specifications, and performance. Furthermore, the analysis highlighted the presence of environmental product certifications and key attributes for evaluating product compliance with sustainability criteria from a life-cycle perspective, such as durability, environmental impact, and features related to installation and disassembly.

2.3. Comparison Between the Observed Building Products and Sustainability Criteria for Material Selection

As previously mentioned, the interventions carried out under the SINFONIA project adhered to the KlimaHaus R protocol, which is specifically designed to evaluate the energy performance of buildings undergoing renovation. However, this protocol does not account for the environmental impact of materials. Consequently, this study references the KlimaHaus Nature protocol, proposed by the KlimaHaus Agency, which is compatible with the existing certification framework.

The KlimaHaus Nature Technical Guideline, particularly in the section titled "Environmental Impact of Building Materials", introduces the ICC indicator. This indicator calculates the environmental impact of building materials and products used in the building envelope through a dedicated calculation program. The ICC indicator evaluates four parameters: Non-renewable Primary Energy (PEI nr), Acidification Potential (AP), Greenhouse Effect Potential (GWP100), and Material Durability (Time of Use, tu).

For specific values of environmental parameters, reference is made to data available in the KlimaHaus database. Where a material is not included in the database, similar materials are used as substitutes. If the product being evaluated has an EPD compliant with ISO 14025 [70] and EN 15804 [71], the certified environmental parameter values in the declaration can be directly input into the calculation program.

The calculation program assigns bonus points for factors such as the proximity of production, processing, and supply sites to the construction site; the use of materials with third-party environmental certifications (environmental product label Type 1 according to ISO 14024 [72]; and materials produced in facilities certified with the Klima Factory label. Additionally, the Guideline specifies materials that are not permitted for Nature

certification, such as products containing ozone-depleting substances, plastics with heavy metals or organic tin compounds, and tropical wood lacking FSC or PEFC certification.

The KlimaHaus Nature indicators for building materials are summarized in Table 2 (see Section 1.2). Based on these criteria, the technical characteristics and product certifications contributing to the fulfillment of these requirements were highlighted in the data sheets of the materials used in the analyzed projects.

3. Results

The results of the analysis for the three selected case studies, namely Via Marche in Florence (Building 1), Via Palermo (Building 2), and Via Brescia–Via Cagliari (Building 3) in Bolzano, are illustrated below, following the methods and observation criteria described in Section 2.

For each building, the technical solutions implemented to achieve energy efficiency goals were examined, and the building products used were evaluated according to the KlimaHaus Nature protocol.

3.1. Outcomes from the Analysis of Building Renovation Projects

For Building 1 on Via Marche in Florence (Figure 1), in relation to the energy efficiency target, the interventions included thermal insulation of the building envelope and roof.

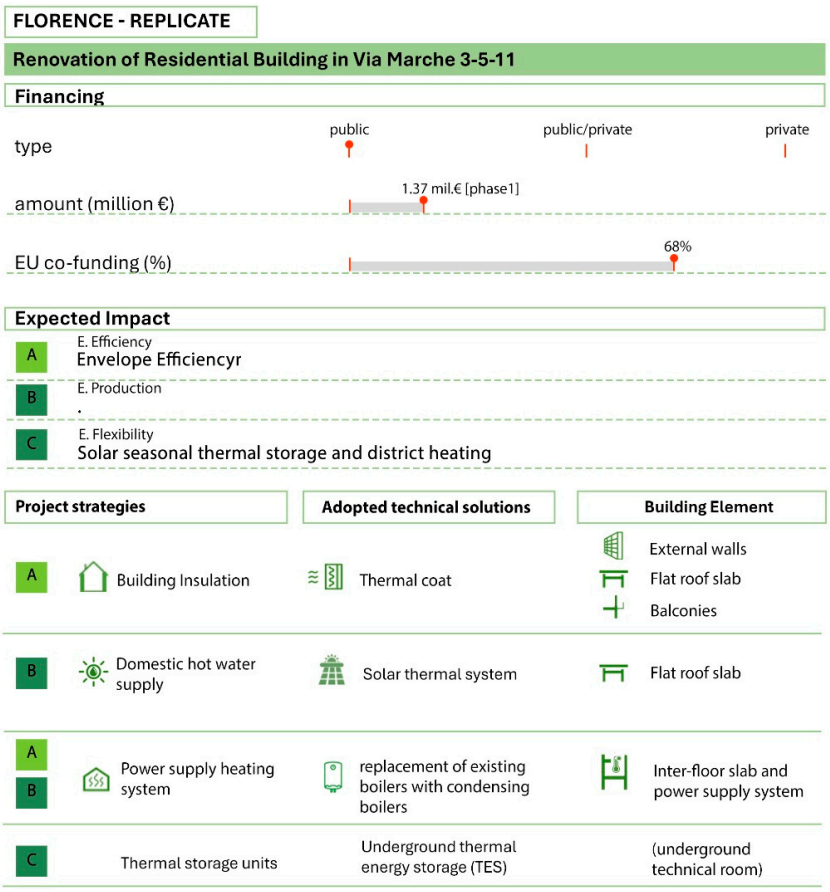


Figure 1. Summary sheet of technical solutions in relation to the three PED targets for Building 1 on Via Marche in Florence.

Active system solutions involved replacing existing heat generators with condensing boilers, upgrading the heating system, and transitioning from single-type heat generation systems to high-performance district heating systems.

In a subsequent phase of the project, the network will reach individual apartments, where the existing boilers will be replaced with small heat exchangers without disrupting

service to tenants. This will benefit residents by reducing maintenance costs and energy consumption.

In terms of renewable energy production, heat will be generated by a cogeneration plant integrated with a solar system installed on the rooftops. A distinctive feature of the project will be the construction of an underground thermal energy storage (TES) unit to store energy for later use in heating (addressing the energy flexibility target).

In Bolzano, for Building 2 on Via Palermo (Figure 2), energy efficiency interventions included passive solutions such as thermal insulation of the building envelope and basement floor, replacement of external windows, installation of shading systems, and the construction of green roofs. Additional solutions involved the installation of mechanical ventilation (MV) systems under the window sills, the introduction of new shafts for the passage of utility ducts, and the rainwater collection system. Furthermore, regarding energy production, the project included the installation of photovoltaic panels and solar panels.

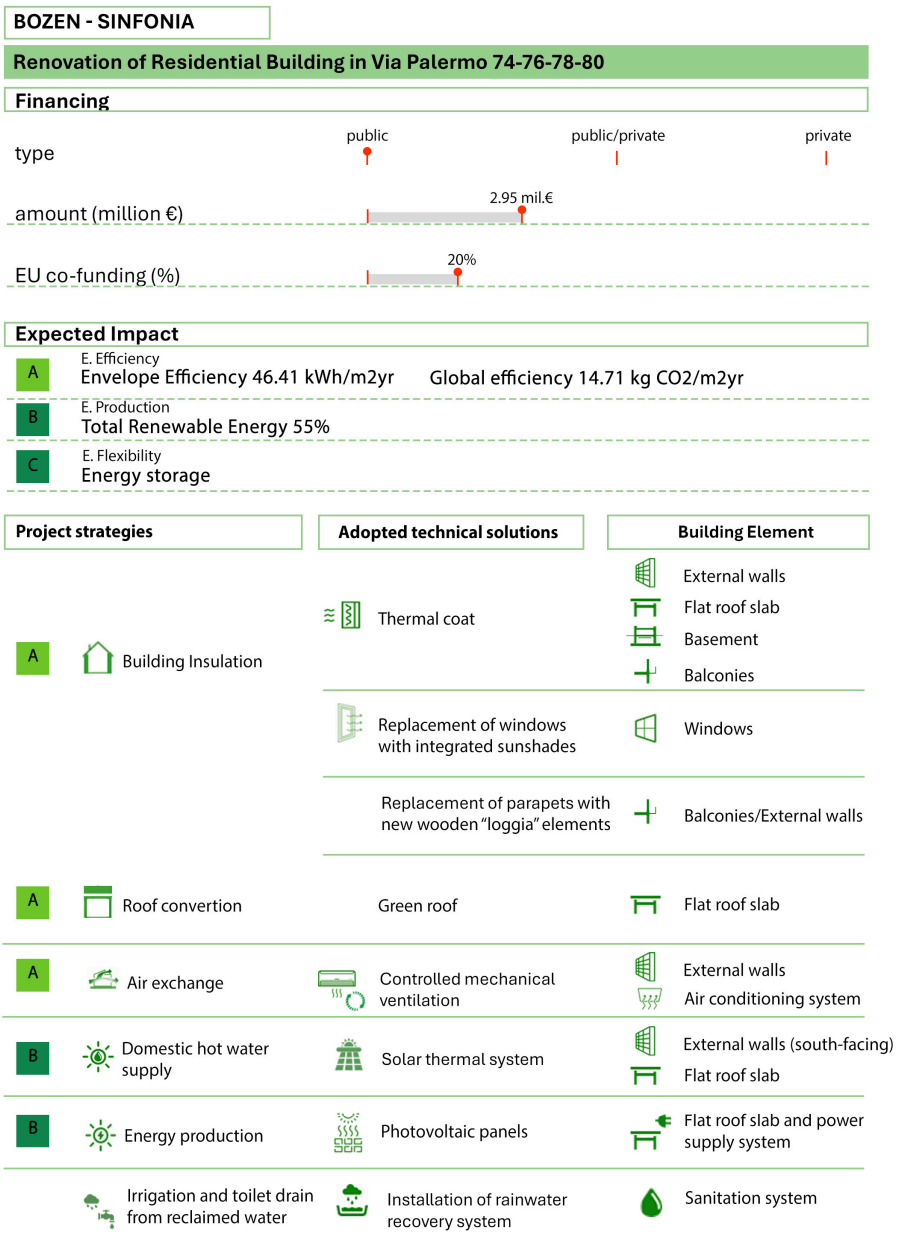


Figure 2. Summary sheet of technical solutions in relation to the three PED targets for Building 2 on Via Palermo in Bolzano.

For Building 3 on Via Brescia/Via Cagliari in Bolzano (Figure 3), passive solutions for energy efficiency included thermal insulation of the building envelope and basement floor, as well as the replacement of parapets and external windows. This project also involved the construction of a wooden elevation using the X-LAM building system. In all apartments, a decentralized mechanical ventilation (MV) system was implemented. Existing apartments retained their radiators, while radiant floor heating was installed in both the new apartments within the wooden elevation and the renovated existing apartments. Additionally, photovoltaic panels and a solar thermal system were integrated into the facade and roof, along with two thermal storage units connected to the district heating network, which is powered by the Bolzano waste-to-energy plant.

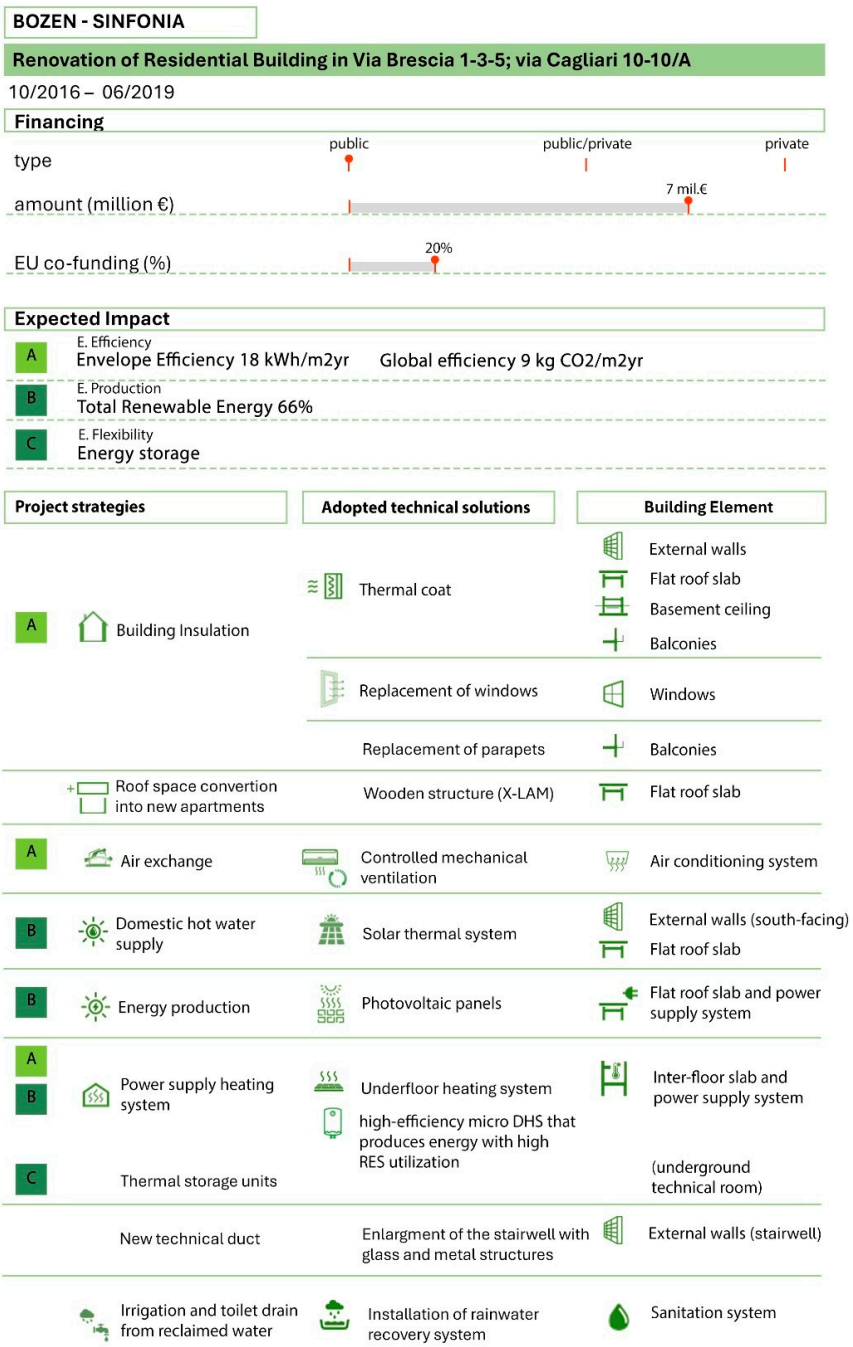


Figure 3. Summary sheet of technical solutions in relation to the three PED targets for Building 3 on Via Brescia–Via Cagliari in Bolzano.

3.2. Construction Features of Recurrent Technological Solutions

Focusing exclusively on passive strategies for energy efficiency, the most recurring technical solutions for envelope insulation were examined in detail.

For Building 1 (Figure 4), the facade insulation was achieved using expanded polystyrene panels with graphite, applied with a mineral binder adhesive and polyethylene sealants. The finish consists of pigmented plaster on fiberglass mesh with a double-polished anchoring base. Mineralized wood wool panels with the same finish were used to frame architectural profiles and window openings. For the terraces, the selected insulation panels were made of expanded polyurethane, combined with the installation of a waterproofing layer and new paving.

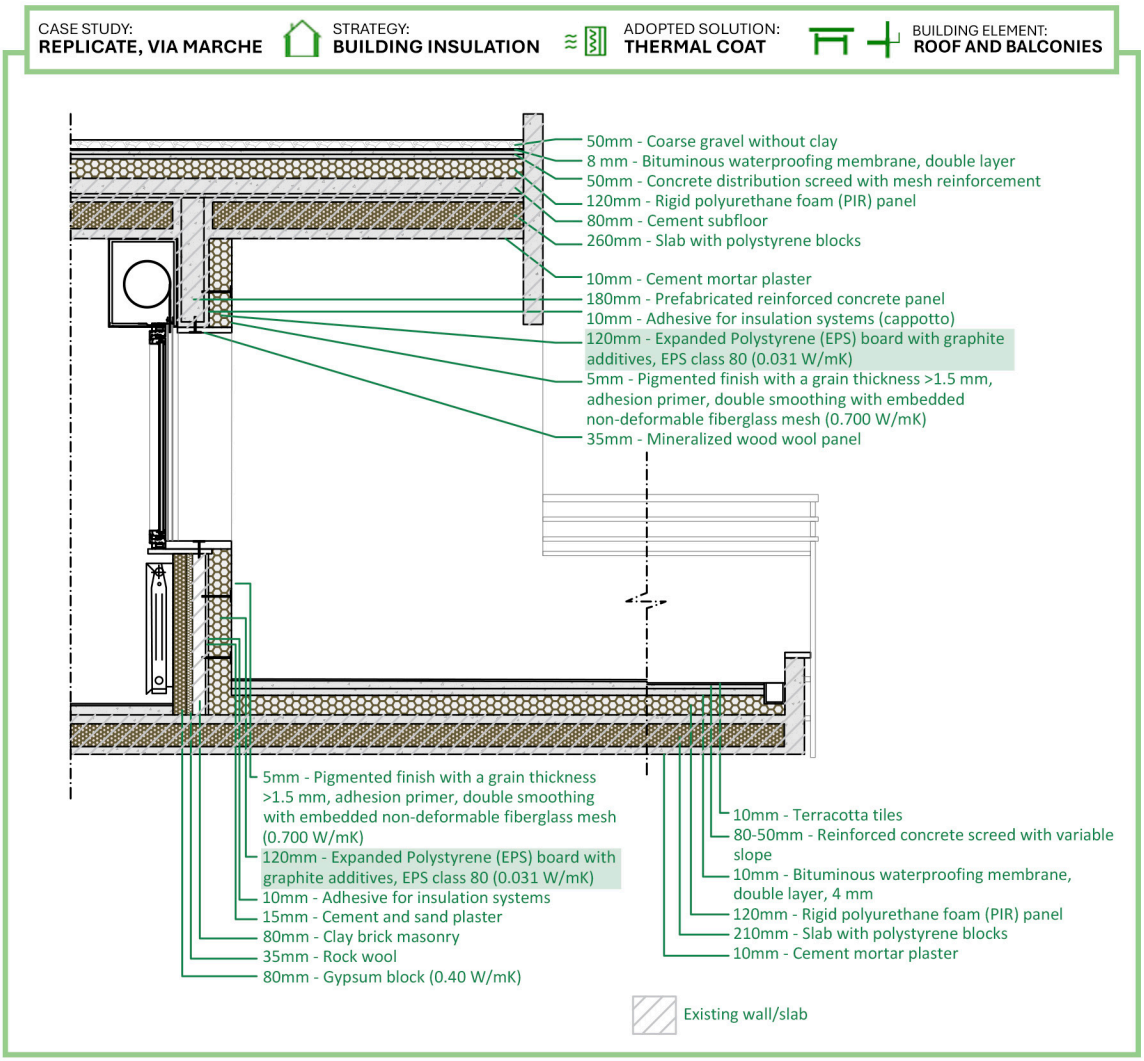


Figure 4. Exemplification of the portfolio of technical solutions for thermal insulation of Building 1 on Via Marche in Florence. Image edited by the authors from original drawings by © CASA SPA.

The intervention did not include replacing the windows but involved replacing the existing roller shutter boxes with new systems featuring integrated insulation.

For Building 2 (Figure 5), the design approach emphasized off-site prefabrication of components, rapid installation/easy disassembly, and the use of dry construction methods applied externally to the building to minimize disruption to tenants.

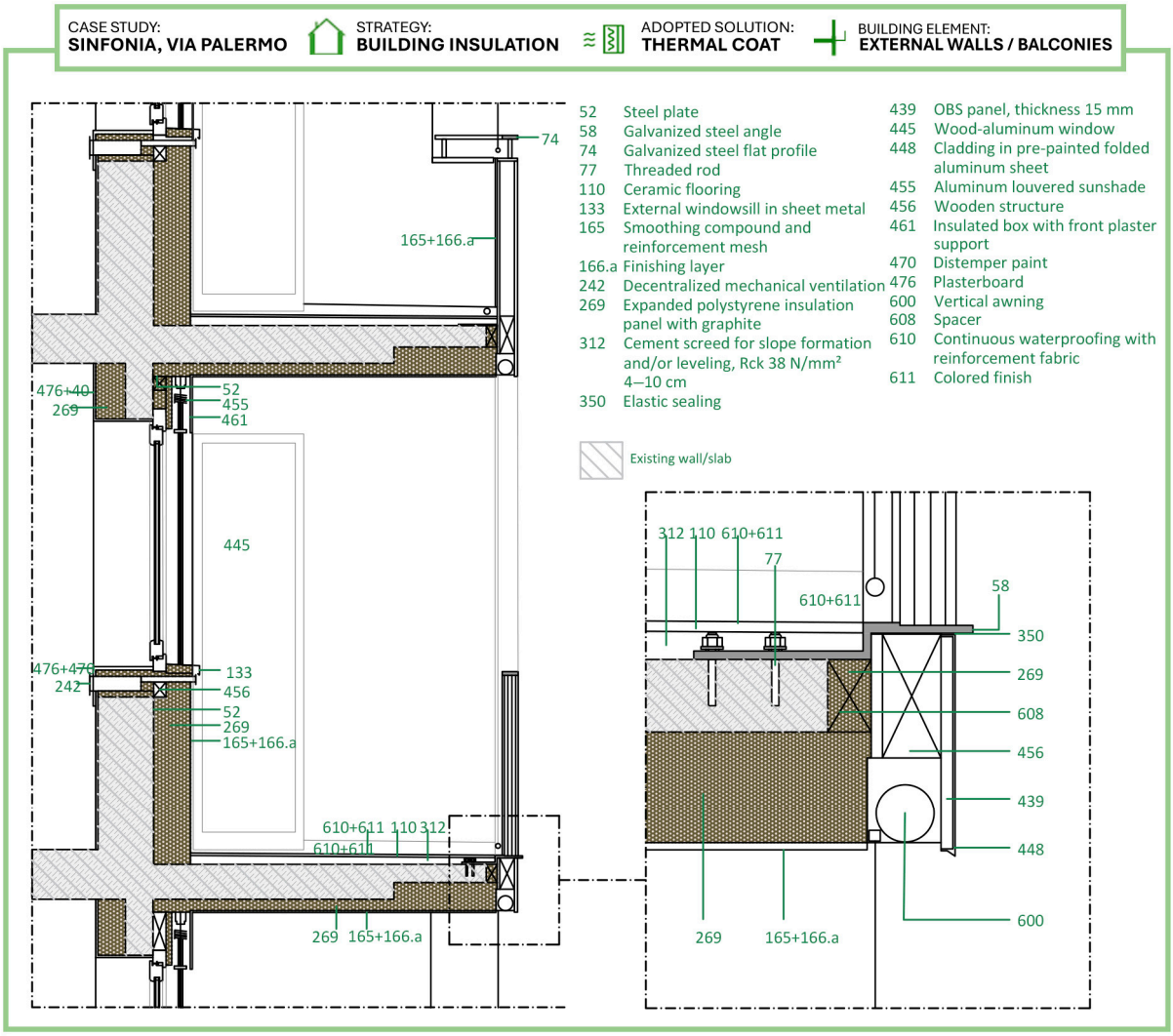


Figure 5. Exemplification of the portfolio of technical solutions for thermal insulation of Building 2 on Via Palermo in Bolzano. Image edited by the authors from original drawings by © Laboratorio di Architettura.

Specifically, window replacement was carried out by anchoring a prefabricated wooden structure to the existing concrete slabs visible on the facade. This structure comprised OSB panels with integrated thermal insulation in expanded polystyrene with graphite, wooden/aluminum windows with low-emissivity double glazing, and an aluminum slatted shading system.

The same system allowed for the integration of decentralized mechanical ventilation (MV) components below the windowsill, as well as external electrical wiring to power them. The external finish consisted of white stapled aluminum panels, while the internal finish was plastered drywall. A similar system was also used for the construction of new balconies.

For Building 3 (Figure 6), on the south-facing facade, the external thermal insulation system consisted of adhered rock wool panels covered by a windproof membrane, interspersed with wooden uprights to which the metal support structure for the solar collectors was anchored.

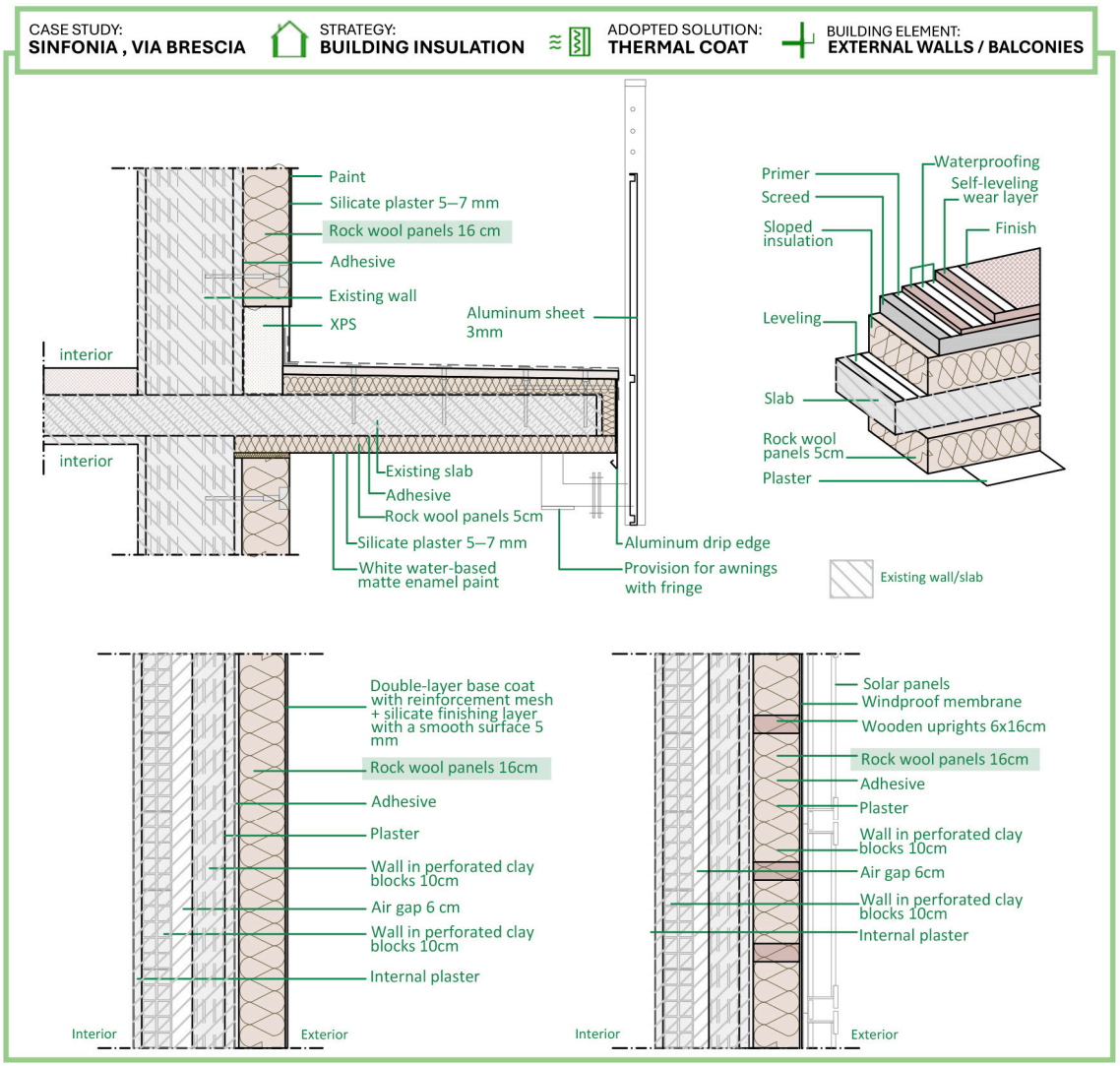


Figure 6. Exemplification of the portfolio of technical solutions for thermal insulation of Building 2 on Via Brescia—Via Cagliari in Bolzano. Image edited by the authors from original drawings by © Studio Tecnico Vettori.

On the other facades, the insulation panels were coated with a smoothing layer, a reinforcement mesh, and a finishing layer in silicate/siloxane paint.

The types of solutions identified were organized according to the involved building element and reported in a portfolio.

3.3. Compliance of Products with Material Sustainability Criteria

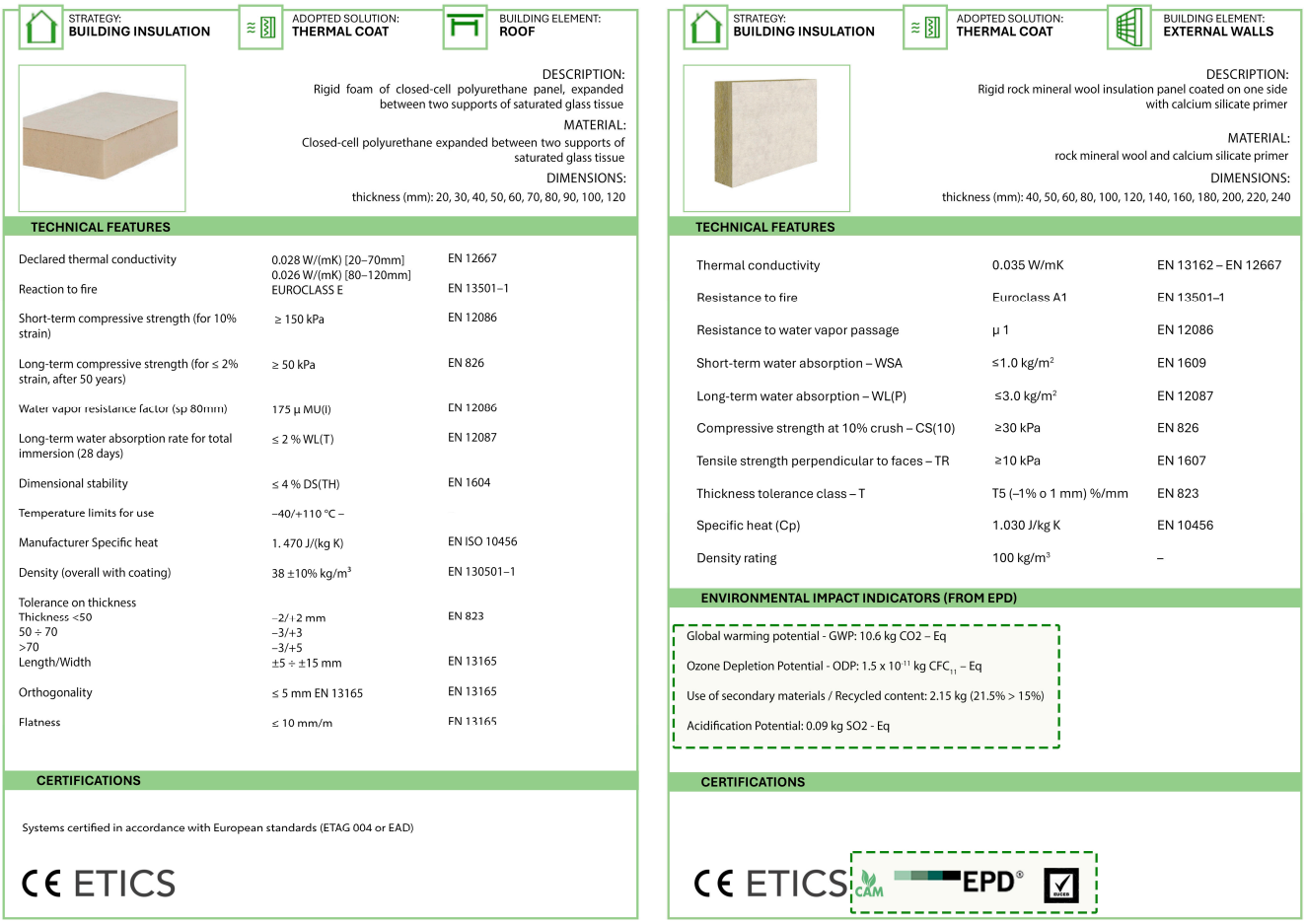
In the context of insulating the external envelope, detailed discussions focused on the construction products used for insulation panels.

In the case of Via Marche in Florence, adherence to ETICS regulations and certification in accordance with ETAG004 were mandated in the procurement documents [73]. For mineralized wood wool panels, eco-compatibility certification by ANAB-ICEA for both materials and production processes, as well as sourcing from sustainably managed forests (PEFC), was required. Expanded foam insulation components were specified to exclude ozone-depleting chlorofluorocarbons (CFCs or HCFCs). Accordingly, a compliant solution utilizing polyurethane panels for thermal insulation was documented in a technical sheet.

For the Bolzano projects, material selection was guided by the Technical Standards defined by the Institute for Social Housing of the Autonomous Province of Bolzano (IPES) [74].

The "Ecology and Sustainability" section emphasized the selection of materials and construction methods based on factors such as the use of renewable resources, low energy consumption during production and transportation, preference for regional resources and products, minimized or eliminated use of solvents, and the utilization of recycled or recyclable materials. Moreover, priority was placed on construction materials with low disposal costs.

To facilitate management during the use phase and component recovery at the end of life, the standards recommended durable products with low cleaning and maintenance requirements, clear differentiation of materials with varying lifespans, and designing structural elements, systems, facades, and finishes as separate components to enable easier recovery and restoration. Similarly, the technical features of the insulating rockwool panels retrieved from the Bolzano projects' technical documentation were summarized. A comparison of the two products is presented in Figure 7.



(**a**) (**b**)

Figure 7. Comparison of data sheets of insulation materials used and selection criteria for sustainable materials between (**a**) Building 1 Via Marche in Florence and (**b**) Building 3 Via Brescia–Via Cagliari in Bolzano.

The comparison revealed that in the Bolzano case study, the products align with the documentation required to verify compliance with the KlimaHaus Nature protocol. The Bolzano project serves as a notable example of environmental sustainability, showcasing a process where maximum transparency regarding material impact—mandated by product life cycle quality certifications—ensures higher quality technical solutions aligned with the philosophy of transitioning to PEDs.

4. Discussion and Conclusions

This study analyzed the role of green building certifications and material selection criteria in facilitating the transition toward PEDs. Through a document review and the examination of three Italian case studies—particularly residential retrofitting projects in Bolzano and Florence—key technical solutions were identified to meet PED objectives: energy efficiency, renewable energy production, and energy flexibility. The findings enabled a comparison of the construction characteristics of the adopted technological solutions with the criteria outlined in green certification systems, highlighting the relevance of voluntary protocols in supporting the environmental sustainability goals of PEDs.

Adopting criteria based on specific indicators proposed by these protocols was found to significantly reduce the environmental impact of building interventions, particularly through passive energy efficiency solutions. The Bolzano case, for example, illustrates how certifications like KlimaHaus can align with Italian regulatory frameworks, particularly the Minimum Environmental Criteria (CAM), enhancing transparency and traceability in material selection. This alignment strengthens the social and institutional credibility of PED-related interventions while supporting broader sustainability goals.

Green building certifications have evolved from simple acknowledgments to powerful tools for incentivizing sustainability. They raise awareness, influence design decisions, offer economic benefits, and foster energy performance monitoring. Furthermore, future PED-specific certification systems could integrate dedicated material selection criteria to promote greater sustainability. This study underlines the importance of adopting GBRS-based material selection criteria as a promising practice for ensuring sustainable and efficient interventions in energy retrofitting projects.

Despite these contributions, the study presents certain limitations. The analysis relied exclusively on documentary sources available in Italian, as the data primarily originated from local administrations and planners involved in PED projects. Additionally, the number of case studies was limited, reflecting only a partial view of the diverse international experiences related to PED transitions. Lastly, the study focused on insulating materials, leaving room for further exploration of other building components.

Nevertheless, this research revealed several key insights. To facilitate the transition toward PEDs, it is advisable for building interventions to follow GBRS criteria in material selection. Certification protocols can play a significant role in energy retrofitting projects by increasing the likelihood of employing sustainable materials. Future PED-specific certification systems should integrate criteria dedicated to material selection, further enhancing sustainability in such projects.

In conclusion, this study contributes to the scientific debate on PED transitions by offering a methodological framework that, with appropriate adjustments, could be extended to international contexts. Future research could expand the focus to include other building components, conduct comparative analyses with international examples, and refine material sustainability indicators for inclusion in future PED-specific certifications.

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WP1, LA1.33 Analysis and state of the art of projects and programs facilitating the transition of local authorities towards climate neutrality. State of the art on project assessment indicators.

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Abbreviations

The following abbreviations are used in this manuscript:

AP	Acidification Potential
ANAB	National Association for Green Building Architecture
BREEAM	Building Research Establishment Environmental Assessment Method
BPDO	Building Product Disclosure and Optimization
CAM	Minimum Environmental Criteria
CLP	Classification Labeling and Packaging
CFC	Chlorofluorocarbons
CO2	Carbon Dioxide
EPD	Environmental Product Declarations
ETICS	External Thermal Insulation Composite System
EU	European Union
FSC	Forest Stewardship Council
GBRS	Green Building Rating Systems
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPP	Green Public Procurement
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
ICEA	Institute for Ethical and Environmental Certification
ICT	Information and Communication Technology
IPES	Institute for Social Housing of the Autonomous Province of Bolzano
KPI	Key Performance Indicators
LCA	Life Cycle Assessment,
LEEAD	Leadership in Energy and Environmental Design
MV	Mechanical Ventilation
NSA	Neighborhood Sustainability Assessment
ODP	Ozone Depletion Potential
OSB	Oriented Strand Board
PED	Positive Energy Districts
PEI nr	Non-renewable Primary Energy
PEFC	Program for the Endorsement of Forest Certification
SVHC	Substances of Very High Concern
TES	Thermal Energy Storage
ZEN	Zero Emission Neighborhood

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