The Circular Adaptive Reuse Project of Cultural Heritage Buildings in Salerno (Italy): from Abandoned Assets to nZEB Buildings

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Abstract. The construction sector has a significant impact on urban pollution, causing an important amount of CO_2 emissions. However, existing building reuse, with a circular economy perspective, can play a crucial role in the energy transition, thanks to the adoption of energy-efficient projects. This paper investigates how innovative technologies and bio-based materials in building reuse can reduce operational CO_2 emissions, while highlighting their potential for long-term energy savings and operational costs reductions. In this perspective, is presented the adaptive reuse project of the historic Monastery of San Pietro a Maiella and San Giacomo in Salerno, in Italy. The study employs a mixed-method approach, combining Energy Performance Analysis, Material Innovation Assessment and Cost-Benefit Evaluation to assess the potential benefits of a circular adaptive reuse of the historic building.

Keywords: Reuse of cultural heritage · Circular economy · Biomaterials · nZEB buildings (Nearly Zero-Energy Buildings)

1 Introduction

The built environment is recognized as one of the sectors that contribute to urban pollution due to the use of materials, energy, and manufacturing technologies. On average, the building stock, throughout its lifecycle construction, operation, and demolition produces 36% of annual CO_2 emissions, 40% of energy consumption, and 50% of raw material extraction in Europe [1, 2].

However, the reuse of the built environment, according to the circular economy perspective, has the potential to contribute to the energy transition through the implementation of energy-efficient building projects that combine the use of renewable energy technologies as well as innovative materials such as nanomaterials and biomaterials [3, 4].

In particular, cultural heritage adaptive reuse contributes to the recovery of existing buildings by minimizing raw materials extraction and soil consumption; but, as cultural

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resources, the regeneration of cultural values represents an additional and relevant benefit in a broader circularity perspective. In general, adaptive reuse of cultural heritage, within the context of the circular economy, aims to achieve different objectives, including the preservation of cultural significance, economic feasibility, environmental regeneration, social cohesion, community welfare, and local economic growth [5].

The objective of this paper is to present the adaptive reuse project of the former Convent of San Pietro a Maiella and San Giacomo in Salerno (Italy), which was carried out in the city of Salerno, Italy. Specific green technologies and materials were used for the design project. The primary aim is to understand how these materials can contribute to a significant reduction of CO_2 emissions in the environment, but more importantly, how the building's operational costs can decrease over time.

The CNR, in collaboration with the Municipality of Salerno, the EBRIS Foundation, and the Pegaso Telematic University, presented this reuse project called "Hub di innovazione città circolare della salute" within the context of the "Expression of interest Ecosystems of innovation in Southern Italy - Interventions for the redevelopment and re-functionalisation of sites for the creation of ecosystems of innovation in Southern Italy" as part of the PNRR call for projects (National Recovery Funds).

2 New Materials and Technologies for the Adaptive Reuse of Historic Buildings

In this paragraph, an overview of new materials and technologies currently used for the adaptive reuse of historic buildings is presented, based on recent studies and reports, including relevant case studies.

To achieve the status of "Nearly Zero-Energy Buildings" (nZEB), nanomaterials and biomaterials can be effectively used [1]. Moreover, innovative technologies for cultural heritage circular reuse and renovation can be applied, including the so-called "Nature Based Solutions" (NBS).

Sustainable and circular projects for the reuse of historic buildings can provide an important boost to cities' ecological transition. It is important that these projects adhere to the principles of circular design, where the use of biomaterials and new technologies plays a key role in the development of nZEB.

By 2030, the European Commission has recommended that buildings move from the current nearly zero-energy buildings to zero-emission buildings [6].

NZEB buildings are designed and built to minimize energy consumption by employing renewable sources for energy production, high-performance materials, and innovative technological solutions [7, 8].

In this perspective, nanomaterials (ENM), such as aerogel, cellulose nanofibers, carbon nanotubes, insulating panels based on nano-composites, etc., are among the most widely used new and innovative materials in the construction sector to realize nZEB buildings. These materials are often used to improve the property of many building materials, including concrete, plaster, glass, tiles, insulating metals, paints, and more. The European Commission defines nanomaterials as natural substances or products comprising particles in a dispersed condition, either as aggregates or agglomerates [9].

Nanomaterials are characterized by small dimensions and differ in physical and chemical properties from traditional materials [10]. Their installation is quick, resulting in a substantial reduction in thermal bridging and the prevention of fungal growth, mould, and moisture. Furthermore, they have excellent resistance to corrosion and fire [10, 11].

Among the innovative materials, biomaterials contribute to developing nZEB buildings. Nowadays, various architectural elements are created using materials such as hemp, cork, wood wool fibres, cellulose, sugarcane, sunflower, peanut, seeds, stalks and leaves, flax, potato, rice, wheat, pineapple, and so on.

These biomaterials are characterized by low thermal conductivity in both hot and cold conditions. They are ideal for extremely humid environments. When compared to other insulation materials, they offer the advantage of absorbing and releasing moisture over time.

In this regard, several studies have investigated the huge potential of these materials [10]. For example, Arup conducts studies on the production of building materials from organic waste processing (from the production of urban bio-waste) [12], which includes microalgae, mushrooms (to realize new bricks), flax, hemp and jute, corn cobs, cellulose, sugarcane, sunflowers, peanut, seeds, stalks and leaves, flax, potatoes, rice, wheat, and pineapple. These materials can be used to produce panels with a variety of shapes and properties by adding water, heat, pressure, and no additives, as needed.

In a report by Interreg Central Europe it is affirmed that the use of new technologies for mapping and monitoring existing buildings, such as recording methods, 3D scanning, electronic tachometry, digital photogrammetry, drone photography, laser scanning, degree photography, visualization techniques 3D, GIS, diagnostic methods, thermography, damage inspection, nuclear magnetic resonance, thermal analysis, etc., is becoming more frequent to realize nZEB buildings [13].

Moreover, photovoltaic systems are among the innovative technologies for renovating existing buildings, used to create nZEB buildings. Photovoltaic glass, for example, is incorporated in fixtures and absorbs solar radiation to generate electricity while maintaining the building's visual look thanks to a transparent gel containing amorphous silicon. These glasses might be transparent, semi-transparent, or coloured to match the architectural environment. Photovoltaic tiles are also very popular since their colour looks similar to that of terracotta tiles, which facilitates aesthetic and architectural integration in existing buildings.

Finally, Nature-Based Solutions (NBS) are commonly employed on flat roofs and external walls of buildings [14]. This technology consists of low-maintenance sedum-like vegetation. It entails planting essences that can survive in harsh drought conditions and have an elevated rate of regeneration and self-propagation. This technological finish offers several advantages to buildings, including waterproofing protection and microclimate regulation through lower air temperature. In addition, to enhance energy savings, green roofs are often coated with an insulating layer.

3 The Reuse/Reuse Project of the Former Convent of San Pietro a Maiella and San Giacomo in Salerno (Italy)

The reuse project of the former Convent of San Pietro a Maiella and San Giacomo in Salerno (Italy) is part of the "Edifici Mondo" complex in Salerno (Italy). The CNR, in collaboration with the Municipality of Salerno, the EBRIS Foundation, and the Pegaso Telematic University, presented this reuse project called "Hub di innovazione città circolare della salute" within the context of the "Manifestazione di interesse Ecosistemi dell'innovazione nel Mezzogiorno - Interventions for the redevelopment and re-functionalisation of sites for the creation of ecosystems of innovation in Southern Italy" as part of the PNRR call for projects (National Recovery Funds).

Salerno is an Italian municipality with around 130,000 inhabitants in the south of Italy. It is the second largest municipality in the Campania region by population [15].

The "Edifici Mondo" is a complex of four large abandoned historic buildings in Salerno's historic city centre: The San Massimo Palace, the former Convent of San Francesco, the former Convent of San Pietro a Maiella and San Giacomo, and the former Convent of Santa Maria of the Consolazione, which altogether approximately include 20,000 square meters. Despite their size and strategic location in the city centre, they are in dire need of restoration [15].

The regeneration project of "Edifici Mondo" (developed within the Horizon 2020 CLIC project "Circular models Leveraging Investments in Cultural heritage adaptive reuse") aimed to design the redevelopment of these historic buildings in order to revitalise the surrounding urban context. It was proposed to connect the buildings with green pathways and to restore the pedestrian ramps previously used by Benedictine monks. Two of the buildings, in fact, are former convents (Convent of San Francesco and Convent of San Pietro a Maiella and San Giacomo). One of the buildings is the Palazzo San Massimo, a noble building of high prestige with elegant decorations, monumental staircases, and frescoed ceilings.

A participatory design approach was employed to identify the new functions to be assigned to the buildings, which include a research centre, cultural activity spaces, applied research laboratories, coworking spaces, craft workshops, and offices for spin-offs and start-ups. The laboratories and equipment set up in the buildings should be used to foster collaborations among private enterprises, research institutes, and universities, as well as the project's partner promoters, to support the development, experimentation, and implementation of innovative products and services in the medical-pharmaceutical sector and the circular economy. Finally, large areas are reserved for advanced training activities, which are an important component of the Hub's activities related to the development and attraction of human capital, as well as conferences/cultural events capable of engaging the local context and projecting it into an international entrepreneurial and innovation ecosystem [15].

The focus of this paper is on the adaptive reuse project of the San Pietro a Maiella and San Giacomo complex (Fig. 1).

After many inspections, the primary faults with the building have been identified. Specifically, the roofs and floors appear to be severely damaged, with obvious evidence of wear. Furthermore, the facades display signs of water runoff stains and exfoliation phenomena, indicating that the external surfaces have degraded. Partial or complete



Fig. 1. San Pietro a Maiella and San Giacomo complex

plaster detachments have also been discovered, compromising the wall's integrity. The thresholds are frequently missing or damaged, and colour changes and efflorescence are visible, indicating a humid environment conducive to the formation of moulds, mosses, and lichens. The building's windows are in dire condition, with several glass components damaged or missing. Furthermore, condensation stains have been discovered on the upper levels' ceilings, most likely due to an inadequate or complete absence of waterproofing on the roof terrace. The internal walls also show signs of condensation and humidity, indicating infiltrations into the internal spaces. Another issue discovered is the humidity in the shafts, which is caused by infiltrations from existing downspout damage. Finally, the presence of rising damp was discovered, which exacerbates the building's decay.

3.1 Materials and Innovative Solutions Used in the Project

Before moving on to the description of the reuse project, it is necessary to point out that each design choice was influenced both by the need to meet the requirements of the Italian Superintendence for Historic Buildings and by the necessity to use solutions compatible with cultural heritage values conservation, as well as the surrounding historic city context. The choice of specific materials and technologies was carefully conducted, taking into account the compatibility of each single intervention.

The intervention's design was orientated towards defining processes dedicated to optimising energy, plant, and architectural quality and thus towards defining design choices aimed at improving the healthiness and well-being of the occupants, which are currently completely absent due to the level and severity of the degradation observed.

The design, therefore, was developed pursuing the eco-efficiency of the building envelope, optimising, among other things, energy consumption and environmental impact, while also being dedicated to improving the architectural quality of the building, paying particular attention to the maintenance and management aspects of the properties, with the aim of increasing the useful life of the works and individual components. Within the building project, high-performance materials related to the geometries and functionality of the existing envelope were identified, thereby maximising the concept of adaptable and flexible space through the pursuit of eco-systemic quality, resulting in the buildings receiving the nZEB classification.

The individual assumptions and design decisions targeted at improving the building envelope's energy efficiency have been investigated, as well as technological compatibility and implementation and maintenance costs.

Every design choice was also influenced by the necessity to meet the requirements of the Italian Superintendence for historical buildings.

In particular, for opaque vertical partitions, the intervention was chosen not only to maximise thermal performance and thus achieve perfect insulation by addressing the identified issues but also to restore the architectural value of the buildings in question.

Regarding the opaque vertical envelope, the chosen technological solution consists of the use of nanotechnological plasters with very low thermal conductivity (k = 0.06 W/mK), capable of ensuring, with extremely thin layers (on the order of mm), performance comparable to that derived from the application of traditional insulating material panels.

In more detail, nanotechnological plasters are a unique combination of highly insulating and thermo-reflecting materials. The combination of the reflecting power of cellular glass microspheres and "coccio pesto" results in a mass with a high concentration of air cells with strong insulating and reflective properties, capable of retaining the mass's breathability.

However, the aforementioned nanotechnological plasters are only suitable for walls that are accessible from the outside. It was assumed to use, whenever possible, nanotechnological plasters with a thickness of 1.5 cm.

No intervention has been planned on the areas of the walls that are inaccessible due to Heritage authority limits to protect the existing internal architectural components. However, on some portions of walls that are not accessible from the outside and where the aforementioned limits do not apply, it was decided to install insulation from the inside using natural hemp fibre panels (k = 0.038 W/mK) with a thickness of 10 cm. These panels work well in both cold and hot conditions, thanks to their low thermal conductivity and high specific heat, which causes the heat within the material to evaporate quickly. These panels are ideal for extremely humid conditions. In fact, unlike other insulators, hemp absorbs moisture and releases it over time. Its permeable properties prevent the formation of interstitial condensation, resulting in healthy living spaces devoid of bacteria, mould, and microorganisms. Furthermore, hemp fibres are characterised by numerous other environmental benefits, including: 1) they produce oxygen and absorb large amounts of CO_2 from the atmosphere; 2) they are a completely renewable natural fibre; 3) they are a low-energy input crop; 4) they are an environmentally advantageous material, as considering the CO_2 absorbed by the plant during cultivation, their carbon footprint is close to zero (0.138 kg of CO_2-eq); 5) the production of the insulating panel requires modest energy consumption compared to mineral fibre insulators and does not require the use of water and chemical products.

So-called "green roofs" were planned on flat roofs. It is an alternative to existing technologies that involves greening the exterior of the roof slab. A green roof fits all of the structural, mechanical, and thermal requirements of any covering while also providing agronomic and drainage capabilities. It is usually a system that is thin and light enough to be used on roofs and requires minimal upkeep because it includes sedum species that must be able to survive in harsh drought conditions while also having high regeneration

and self-propagation capabilities. It is a technological finish that provides several benefits to the building, including waterproofing protection, microclimate regulation due to lower air temperature in urban environments, combating the heat island effect, reducing the presence of fine dust, creating new habitats for wildlife, and having a lower environmental and aesthetic impact. Furthermore, in line with the green roofs, an insulating material layer has been planned to maximise energy savings. Even in this case, the panels are composed of hemp fibres, which have already been mentioned for their potential. The thickness of the previously indicated covering panels is considered to be 12 cm.

Furthermore, insulation using the same hemp panels was planned for the sloped roofs to be repaired in order to minimise thermal dispersions as much as possible while completely respecting the limits to which the buildings in question are subjected.

Insulating the floors lying on the rock wall or embankments is intended to boost the envelope's thermal performance even further. This intervention provides an efficient barrier against moisture rising from the ground's capillarity, so improving the health of the building and its interior environs. Even in this case, the insulation is made of 10 cm thick hemp fibre panels.

In accordance with the current shapes and colours, thermal break wood-aluminium frames for the fixtures were planned for the transparent vertical components.

Thermal break doors, characterised by very low thermal transmittance values, should be installed for the building's access doors without altering the aesthetic aspect of the existing doors.

To complete the intervention, the use of photocatalytic paints should be applied on all buildings' external perimeter walls. Photocatalytic paints can clean the air of pollutants, which is why they are often called "smog-eating paints". Utilising the photocatalytic process of titanium dioxide nanoparticles (a light-sensitive catalyst), these are capable of acting on nitrogen oxides, the protagonists of the chemical reactions in the atmosphere that produce ozone, and converting them into nitric acid, which is more easily handled. The use of photocatalytic paints contributes to the reduction of air pollution generated by automobile emissions, factories, and domestic heating. In addition, photocatalytic paints not only break down organic and inorganic pollutants that settle on surfaces, but they also function as bactericides and fungicides.

3.2 Plant Interventions and the Use of the Latest Technologies

The project includes a variety of system changes designed to maximise energy and economic savings while minimising environmental effect.

To advance with the size of the plant systems, the thermal characteristics of the building were assessed using a series of simulations to determine the building's thermal demand and, as a result, proceed with the sizing of all the plant systems.

A preliminary design solution was proposed for systems that recover white, grey, and black water.

In terms of water recovery, rainwater collection and reuse are expected to reduce energy consumption and environmental effects while increasing economic convenience. Rainwater is a continuous source that requires simple and cost-effective treatments to be reused for non-potable purposes. Rainwater recovery systems reuse water collected from building downspouts, creating an appropriate reserve for irrigation or service water

outflow. These systems allow for the development of rainwater recovery opportunities, which, rather than being squandered, can be profitably employed for the aforementioned reasons. The proposed system ensures that the rainwater collected from the roof flows into the gutter and is sent to the storage tank after proper filtration (primary filter). Following that, the filtered and collected rainwater in the tank is sent to the utilities via a specific suction machine. The recovered water is used to irrigate green roofs and gardens, as well as to flush toilets and wash machines (where present), and for all other non-potable uses.

It is additionally planned to recover grey water, which refers to water used for personal hygiene. The grey water recovery and reuse technology enables significant reductions in drinking water consumption. In fact, the approved system returns grey water to a hygienic state through the designated system.

Finally, each building will have a system in place to recover black water. An activated sludge plant serves as the foundation of the black water recovery and treatment system. First and foremost, a primary treatment step is required, which involves primary sedimentation in a tank. Next, the pre-treated effluents are biologically oxidised using an activated sludge system, followed by secondary sedimentation downstream of the oxidation system. The treated waters are also planned to be used for filling toilet cisterns, irrigating green areas, cleaning buildings.

The second proposed design solution is for the installation of a ground/water geothermal heat pump, which requires the excavation of a geothermal field through which the system's pipes will pass for thermal exchange with the ground.

The intervention is expected to lower electricity consumption by more than half when compared to typical asynchronous motors.

To complete the plant interventions, an automated system for optimal control and regulation of the building's heat generation system was considered. The system includes external and internal temperature sensors, immersion probes in the pipes, occupancy sensors, twilight sensors, and anemometers in order to measure all the thermodynamic features that contribute to determining thermal and cooling energy requirements. Such sensors can interact with each other thanks to proximity and functionality logics, and they are all linked to a central gateway. The latter, in turn, based on the data measured by the sensors, having memory of similar past situations, sends commands to the actuators in order to minimise not only the energy needs due to the system but also the discomfort of the occupants, thereby maximising the thermo-hygrometric well-being conditions within each building.

3.3 Renewable Sources and Photovoltaic Systems

In terms of the photovoltaic systems that will be built, a novel technique that is not architecturally obtrusive was designed: photovoltaic tiles on sloped roofs.

This technology allows the most efficient use of renewable sources while preserving the aesthetic appearance of buildings. As a result, according to the authors, its usage is permissible even in the presence of Heritage protection regulations limitations, provided that the restrictions for the buildings in question in this paper are strictly followed.

To properly design each of the plants, the design principle employed is to maximise the capture of the available annual solar radiation.

The proposed modules operate on the premise of low molecular density. Each module is made of a non-toxic, recyclable polymer compound that can absorb photons. The module has standard monocrystalline silicon cells with an efficiency of roughly 12%. The surface seems opaque, but it is transparent to sun rays, allowing solar energy to power the cells.

The photovoltaic tiles have no impact on the artistic and architectural value of the buildings on which they are installed. As a result, the building's sloped roofs will be completely refurbished with such solar tiles. Furthermore, the planned photovoltaic tiles, like the paints for the facade, have a photocatalytic effect, which considerably improves the overall air quality.

4 Results Obtained in Terms of Improving the Energy Performance of the Building Through the Use of Photovoltaic Technologies

To evaluate the building's energy performance (also in terms of costs), the study employed an integrated approach combining Building Information Modeling (BIM) (used for the entire architectural design) with Termus software (Acca Software) for dynamic thermal-energy simulations. This methodology enabled systematic analysis of the monastery's energy behavior, based on the proposed design solutions. This allowed to estimate operational energy consumption and costs for different design options, supporting the adaptive reuse design team in the choice of the most satisfactory solutions in terms of environmental performances, as well as heritage values conservation. The integration of innovative materials and technologies with cultural heritage was one of the key aspects considered for the choice of the final solution.

In terms of energy performance, the proposed interventions for reusing the historic buildings of San Pietro a Maiella and San Giacomo allow for significant energy savings. Furthermore, due to compliance with the minimal coverage from renewable sources, the building has achieved the nZEB classification, fully respecting the Italian Superintendence's requirements.

The key findings in terms of renewable energy coverage are presented below.

The adaptive reuse project of the convent of San Pietro a Maiella and San Giacomo first demonstrates how a planned photovoltaic system partially meets the requirement for electrical energy for heating services (see. Fig. 2). As expected, in the months of December and January, when thermal demand is particularly high and the photovoltaic system's productivity is lower due to reduced solar irradiation, the amount of electricity drawn from the national grid is significantly higher than that produced by the system and self-consumed. In the months of November and February, when external climatic conditions are generally less harsh and there is more intense irradiation, the difference between the electricity produced and self-consumed for heating purposes and that obtained from the grid for the same service is lower. Finally, during the month of March, usually with milder external temperatures, the electricity produced and self-consumed for heating is even higher than that supplied by the electrical grid.

Regarding the cooling service, in Fig. 2 it is possible to observe how this service is primarily provided by the electrical energy generated by the photovoltaic system planned for the roof. This is made possible by the significant solar radiation values

that characterise the months when refrigeration energy for the cooling service is higher in demand, as well as the planned photovoltaic system's peak size. More specifically, the solar system provides the majority of the cooling service between the months of April and August. In the month of September, however, there is a significant need for electricity from the national power system. Finally, throughout the month of October and, therefore, in the lead-up to the start of the heating season, demand is fulfilled mostly through grid electricity, with the photovoltaic system supplying the remainder. This is explained by the fact that, as previously observed, during the months of the heating season, the intensity of solar radiation is lower, and as a result, the productivity of the photovoltaic system is lower.

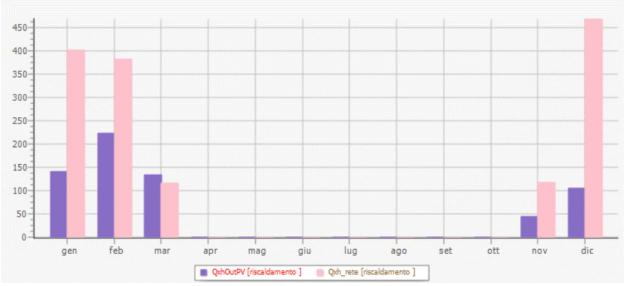

Fig. 2. Monthly self-consumed energy or obtained from the grid for heating service according to the radiation expected per month

Regarding the service of producing hot water for sanitary use DHW (Domestic Hot Water), the situation is roughly similar to that of the heating and cooling services (see Figs. 3, 4). In detail, during the colder months, the electricity produced and self-consumed to meet this service is less than that obtained from the electrical grid; however, during the warmer months, the same service is predominantly met through the electricity generated by the photovoltaic system. The only exception is the months of September and October. In fact, during the first month, significant integration from the national electricity grid is required, as the photovoltaic system's electricity cannot cover the complete requirement for DHW production. In contrast, during the second month, the share obtained from the electrical grid is more than that produced by the photovoltaic system (see Figs. 3, 4).

Overall, renewable sources account for 80.3% of heating, cooling, and residential hot water generation.

Figures 5 and 6 show that during the warm months, from April to September, the lighting service and the movement of people and goods are almost entirely satisfied by the electricity produced by the photovoltaic system, whereas during the cold months, from October to February, the electricity obtained from the grid accounts for a greater share than that produced on-site. The sole exception is the month of March. In March, the self-consumption and grid withdrawal components were similar, with the former somewhat greater than the latter.

Figure 7 depicts the monthly renewable energy coverage for all of the services described above. In detail, renewable energy sources provide for more than 70% of heating service, peaking at 80% in March. The cooling service coverage varies greatly

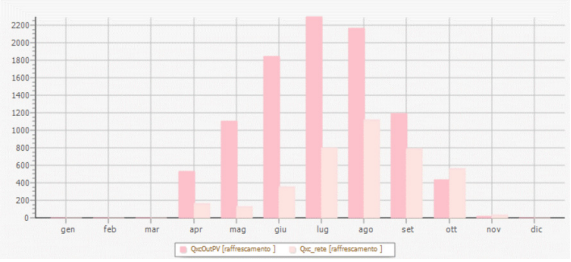

Fig. 3. Monthly self-consumed energy or obtained from the grid for cooling service

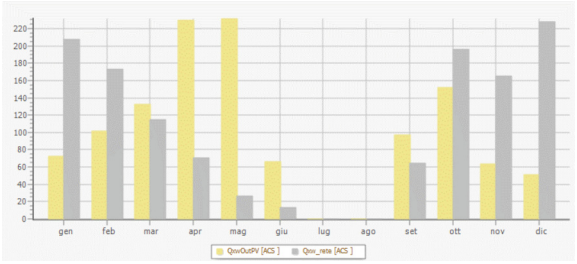

Fig. 4. Monthly self-consumed energy or obtained from the grid for DHW service

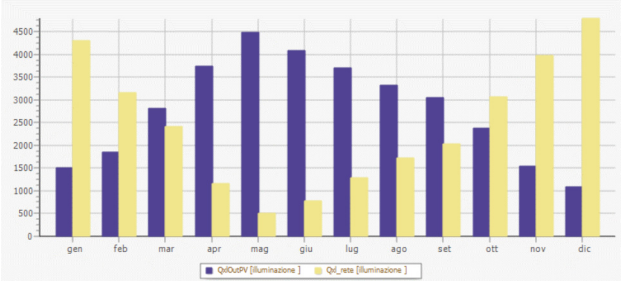

Fig. 5. Monthly self-consumed energy or obtained from the grid for lighting service

throughout the year, ranging from 30% in the cooler months to peaks just above 80% (May). In terms of DHW production, renewable sources meet more than 80% of the whole requirement throughout the year, with peaks near 100% between May and August. Regarding lighting and the movement of people and goods, it is possible to observe that renewable sources are largely covered during the warmer months, when incident solar radiation is stronger, while only marginally during the colder months. Specifically, the coverage ranges from around 30% of the demand during the months of January and December to slightly more than 80% in May.

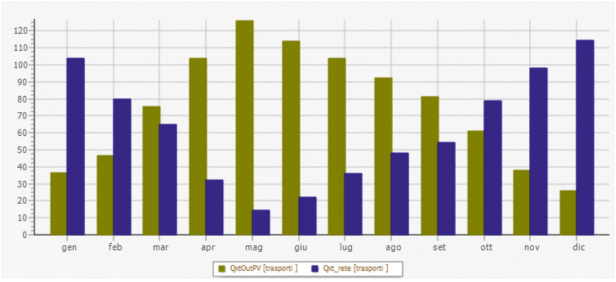

Fig. 6. Monthly self-consumed energy or obtained from the grid for movement of people and goods service

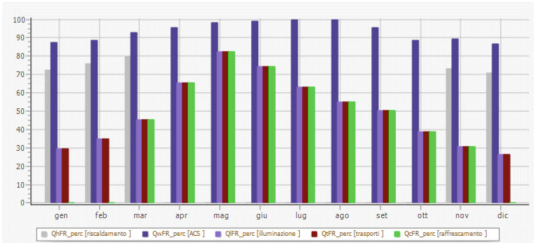

Fig. 7. Monthly renewable sources coverage for all services

4.1 Analysis of Avoided Costs and CO_2 Reduction in the Environment Due to the Use of Photovoltaic Technology Sample

After conducting a thorough cost analysis of each intervention for the reuse project of the former Convent of San Pietro a Maiella and San Giacomo (using Termus and Primus software of Acca Software), the total cost amounts to €5,490,265.60 (the water-sanitary system cost €332,537.58, the thermal system cost €1,052,994.19, the electrical system cost €2,402,787.01, and the thermal insulation required an investment of €1,523,064.60).

After moving beyond this purely economic analysis, the focus shifted to understanding how the use of innovative technologies and specific green materials can produce remarkable results in terms of energy savings (reduced CO_2 emissions) and operational costs associated with the building's functioning.

In particular, the transition to photovoltaic technology resulted in a 30% reduction in building heating operational costs. In reality, without the contribution of photovoltaics, the operating cost for heating would have been approximately €533.60 (per year), however with the use of solar energy, the actual cost has decreased to €371.22, resulting in an economic saving of €162.38 (Table 1). This saving demonstrates how photovoltaics can reduce the cost impact of a fundamental utility, such as heating.

Regarding the production of domestic hot water (DHW), photovoltaics had an even more significant impact. If the cost of producing domestic hot water (DHW) without photovoltaics have been €614.28 (per year), the adoption of solar technology has lowered the cost to €314.73, with a savings of €299.54, or nearly 49% of the original

costs (Table 1). This finding validates photovoltaics' effectiveness in boosting energy efficiency in household hot water production.

Instead, photovoltaics have significantly reduced the cost of cooling the structure by 71%. Prior to the implementation of photovoltaics, the cost for cooling was €3,379.92 (per year), but thanks to the energy produced by the panels, it was reduced to €987.98, resulting in a savings of €2,391.95. This finding indicates photovoltaics' high efficiency in environments with high energy demand (see Table 1).

Even for lighting, photovoltaics have had a significant impact, lowering costs by over 50%. Without solar energy, the cost for lighting would have been €15,685.79 (per year), but with the adoption of photovoltaics, it has decreased to €7,301.65, resulting in an economic saving of €8,384.14 (see Table 1). In this case, photovoltaics had the greatest economic impact, demonstrating its ability to significantly reduce costs.

Overall, the use of photovoltaic technologies has resulted in a total economic savings of €11,464.17, reducing overall costs from €20,626.40 to €9,162.23, with a cost reduction of 55% for each calendar year.

Besides the economic benefits, the adoption of photovoltaic panels has also had a positive impact on CO_2 emissions reduction.

In particular, CO_2 emissions from the facility's heating operations, were reduced from 1,511.15 kg to 1,051.30 kg (per year), a decrease of 459.85 kg. Although the economic savings from avoided emissions were minor (€36.79), the photovoltaic system still contributed to improve the system's energy efficiency (Table 2).

In the case of the production of domestic hot water (DHW), CO_2 emissions have significantly decreased from 1,739.63 kg to 891.32 kg (per year), with a reduction of 848.30 kg, thus generating an economic saving of €67.86 (Table XX). This reduction in emissions confirms the efficiency of photovoltaics in this area, where significant economic savings have been achieved.

Cooling had the greatest reduction in CO_2 emissions, dropping from 9,571.94 kg to 2,797.95 kg, representing a reduction of 6,773.99 kg, or almost 71%. This resulted in an economic saving of € 541.92, highlighting the importance of photovoltaics in high-energy-consuming applications such as summer cooling (Table 2).

CO_2 emissions from lighting have drastically decreased from 44,422.14 kg to 20,678.26 kg (per year), a reduction of 23,743.88 kg (Table 2). This led to a €1,899.51 cost savings, demonstrating the efficacy of photovoltaics in this area and significant economic benefits.

4.2 Analysis of the Results of the Entire Adaptive Reuse Project of the Former Convent of San Pietro a Maiella and San Giacomo

The reuse project of the former convent of San Pietro a Maiella and San Giacomo, according to the principles of the circular economy, yielded very significant results, both environmentally and socio-economically, demonstrating the efficacy of an intervention aimed at combining heritage preservation with technological innovation. One of the most notable outcomes has been an improvement in air quality and living comfort for future building users as well as residents living near the historic building. The building will benefit from optimised ventilation management while reducing thermal fluctuations within the spaces as a result of the adoption of advanced energy solutions, such as thermal

Table 1. Costs avoided by using photovoltaics for building operation

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Service	Total electricity demand [kWh]	Electricity from the grid [kWh]	Electricity produced by photovoltaic [kWh]	Operating cost (in absence of PV)	Actual operating cost (with PV)	Cost savings guaranteed by PV
Heating	2.134,39	1.484,88	649,51	€ 533,60	€ 371,22	€ 162,38
DHW	2.457,10	1.258,93	1.198,17	€ 614,28	€ 314,73	€ 299,54
Cooling	13.519,69	3.951,91	9.567,78	€ 3.379,92	€ 987,98	€ 2.391,95
Lighting	62.743,14	29.206,58	33.536,56	€15.685,79	€ 7.301,65	€ 8.384,14
Transport	1.651,26	746,62	904,64	€ 412,82	€ 186,66	€ 226,16
TOT	82.505,58	36.648,92	45.856,66	€ 20.626,40	€ 9.162,23	€ 11.464,17

Table 2. CO_2 emissions reduction due to energy use

CONVENT OF SAN PIETRO A MAIELLA AND SAN GIACOMO						
Service	CO_2-eq emissions (in the absence of PV) [kg]	Actual CO_2-eq emissions (with PV) [kg]	CO_2 emissions avoided thanks to PV [kg]	Cost of CO_2 emissions (in the absence of PV)	Cost of actual CO_2 emissions (with PV)	Savings due to avoided CO2 emissions thanks to PV
Heating	1.511,15	1.051,30	459,85	€ 120,89	€ 84,10	€ 36,79
DHW	1.739,63	891,32	848,30	€ 139,17	€ 71,31	€ 67,86
Cooling	9.571,94	2.797,95	6.773,99	€ 765,76	€ 223,84	€ 541,92
Lighting	44.422,14	20.678,26	23.743,88	€ 3.553,77	€ 1.654,26	€ 1.899,51
Transport	1.169,09	528,61	640,49	€ 93,53	€ 42,29	€ 51,24
TOT	58.413,95	25.947,44	32.466,52	€ 4.673,12	€ 2.075,79	€ 2.597,32

and acoustic insulation, via specific biomaterials and nanomaterials analysed in paragraph 3.1, 3.2, 3.3. This will contribute to a healthier and more habitable environment, increasing the well-being of future users.

Moreover, future users will see clear economic benefits, including a significant reduction in energy bills. The integration of photovoltaic panels and the overall efficiency improvement of the building (see paragraph 3.3) will greatly reduce the energy consumption obtained from the grid, resulting in huge cost savings.

Furthermore, the convent's reuse project will have a good impact on the urban setting in which it is located, as it will boost the beauty of the neighbourhood while also contributing to the development of the microclimate.

The reuse of the historic building has the potential to reignite interest in the neighbourhood, drawing visitors and opening up new prospects for local investment. The integration of sustainable solutions, in terms of technologies and new materials, as well as the focus on preserving the architectural heritage, will make the neighbourhood more interesting and vibrant, fostering urban renewal that will also benefit the local economy.

In parallel, since the phase of defining the new functions to be attributed to the building was shared with the community, a process of raising awareness among the interested stakeholders has been observed in terms of increasing their awareness of the importance of reuse and energy efficiency of historic buildings, emphasising how it is possible to preserve cultural heritage without compromising sustainability and residential comfort. This has stimulated a broader discussion on the necessity of sustainable practices in historic building management, both locally and among professionals.

Finally, one of the most significant objectives of the project was to transform the historic building into zero-energy building. It will be able to reduce energy consumption and corresponding CO_2 emissions by implementing technologies such as photovoltaics, enhanced thermal insulation, and high-efficiency heating and cooling systems, attaining a high level of energy self-sufficiency. This has been a significant step not only towards environmental sustainability but also towards fulfilling global emission reduction targets and transitioning to a low-carbon future.

5 Conclusions

The pressing environmental and social issues of our day necessitate novel methods. This also concerns the cultural heritage sector, to exploit its potential as an engine of sustainable growth and long-term prosperity for people, the planet, and places [16].

The building sector, responsible for a large amount of CO_2 emissions, is critical in fighting climate change. Reusing historic buildings in accordance with circular economy principles represents a solution capable of contributing to urban ecological transition. The adaptive reuse project of the former Convent of San Pietro a Maiella and San Giacomo in Salerno has demonstrated how integrating innovative technologies and eco-sustainable materials can drastically cut CO_2 emissions and long-term operational costs.

The use of photovoltaic panels, in particular, proved to be critical in improving the building's energy efficiency, resulting in considerable economic savings and emissions reductions across all operational aspects, including heating, sanitary hot water generation, cooling, and lighting.

Furthermore, the experience of the adaptive reuse project for the Convent of San Pietro a Maiella is a virtuous example of how technological innovation can potentially coexist with historical heritage, offering a replicable model for other building realities while adhering to correct heritage conservation criteria.

The adaptive reuse project has the potential to regenerate an entire historic district of the city of Salerno by defining new functions that have significant economic and social benefits, in line with urban regeneration aims. Urban regeneration initiatives can include

micro, meso, and macro-level interventions, such as revitalising entire neighbourhoods, derelict historical sites, abandoned industrial zones, and other spaces. The purpose of urban regeneration is to revitalise underutilised areas, redistribute opportunities, and ultimately boost urban prosperity and overall quality [17].

This study presents limitations concerning the assessment of environmental and economic impacts, which could be addressed by using more complete assessment tools such as Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). The adoption of these methods would in fact allow the environmental and economic costs to be analysed not only during the building's operation phase, but also during the project's realisation and until the disposal phase [2]. The use of these tools will also make it possible to carry out a comparative analysis of different project scenarios, offering more precise benchmarks and testing opportunities for the proposed solutions.

However, in the preliminary phase, the assessment conducted did provide useful insights for the development of the subsequent phases of the study.

Finally, it is worth to note that environmental performances are not the only criteria for a circular adaptive reuse of cultural heritage, as previous studies demonstrate [18, 19]. In fact, compatibility between historic/cultural values preservation, environmental performances and social value should be realized. Thus, "circular" adaptive reuse projects could be conducted engaging communities and stakeholders in co-design exercises since the early stages of ideation, putting in synergy expert and non-expert knowledge, also considering that actual performances are clearly influenced by users' behaviour. This would ensure that communities are aware of environmental impacts of different options for buildings reuse. Furthermore, early stage co-design would allow that the selected solutions are in line with the community's needs and wishes, as well as with the most advanced technological and cultural preservation criteria.

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