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Self-sufficiency in Panzano Dwellings: A Replicable Model for Environmental, Social, and Economic Sustainability

By Paola Limoncin[*], Carlo Antonio Stival[±] & Thomas Bisiani[•]

The evolution of self-sufficient living offers significant opportunities for environmental, social, and economic sustainability through innovative residential strategies. Domestic self-sufficiency depends heavily on the optimization of household spaces and the integration of resource management technologies. Within this context, relevant experiences address bioclimatic greenhouses integrated into façades and high-performance building envelopes, which improve internal microclimates while substantially reducing energy consumption. Water resource management constitutes another crucial challenge: rainwater harvesting and reuse systems are successfully implemented across European eco-communities, where soilless cultivation techniques enable food self-production for resilient housing. Urban regulations play a decisive role in enabling these strategies, incentivizing the redevelopment of the existing building stock. The Panzano District, in northeastern Italy, serves as a compelling case study adopting an interdisciplinary approach. Historically linked to the Monfalcone Shipyard, the District features worker housing originally designed for efficiency and social functionality. Here, the adoption of passive architectural systems and advanced technologies can reduce the exploitation of raw resources while improving quality of life through reproducible solutions. Thus, self-sufficient living requires both cultural and social transformation, as demonstrated by European examples illustrate how resource and knowledge sharing strengthens community bonds while improving collective well-being. The Panzano case demonstrates that domestic self-sufficiency represents a challenge encompassing architecture, technology, regulation, and society, offering replicable models for sustainable and resilient living.

Introduction

Rethinking Domestic Self-Sufficiency: An Interdisciplinary Approach to Contemporary Living through Greenhouse Architecture

The evolution of self-sufficient living represents a crucial challenge for environmental, social, and economic sustainability, while simultaneously offering opportunities for innovation. This challenge emerges from the necessity to rethink traditional paradigms of dwelling in response to territorial transformation driven by climate change and the dynamics of nomadism and mobility that characterize our time, which now prevail over traditional models of settlement stability. These

[*]Research Fellow, Department of Engineering and Architecture, University of Trieste, Italy.
[±]Associate Professor, Department of Engineering and Architecture, University of Trieste, Italy.
[•]Research Fellow, Department of Engineering and Architecture, University of Trieste, Italy.

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significant changes in how we live and perceive space define a condition of contemporary dwelling, characterized by the continuous redefinition of relationships between public and private domains, as well as between interior and exterior spaces.

The case study of the Workers' District of Panzano, in northeastern Italy, provides a significant context for exploring the potential of domestic self-sufficiency through an interdisciplinary approach that integrates architectural, technological, and social perspectives. The District, historically connected to the Monfalcone Shipyard, features an urban and architectural form characterized by a legacy of worker housing, originally conceived according to criteria of efficiency and the provision of social functions. This heritage represents an opportunity to develop self-sufficiency strategies that combine historical memory with innovative solutions, while addressing the contemporary condition of dwelling that requires flexible responses to mobility and climate change.

The exploration of the greenhouse space is considered crucial for this investigation. We consider it both in its traditional conception as an accessory structure for cultivation, and as an architectural device capable of redefining the domestic threshold through an innovative synthesis between environmental, functional, and climatic characteristics, and between the public and intimate dimensions of interior space. The boundary between domestic and urban dimensions can thus be reconfigured to meet the changing needs of contemporary living, influenced by nomadism and recent climatic trends. These factors have led to the dissolution of traditionally well-defined boundaries between different spatial experiences, giving rise to hybrid configurations characterized by transparency, visual continuity, and functional ambiguity.

The adoption of passive architectural systems with advanced technological content, and bioclimatic greenhouses integrated into building façades in particular, can contribute to reducing energy dependence and improving quality of life. These strategies, already tested in European contexts, can improve the internal microclimate and significantly reduce energy consumption while simultaneously redefining the threshold between interior and exterior spaces. The enhancement of the building envelope through such interventions represents a strategy that addresses both technical performance and the spatial ambiguity required by contemporary living patterns.

Domestic self-sufficiency is closely connected to the quality of household spaces and the integration of technologies for resource optimization. Water resource management constitutes a key element of domestic self-sufficiency, whereby the recovery and reuse of rainwater can be integrated into a sustainable local management system. Additionally, the adoption of soilless cultivation techniques offers innovative solutions for food self-production, contributing to a resilient housing model that responds to the hybrid nature of contemporary dwelling configurations.

The reproducibility of interventions on a district scale, through standardized solutions applicable to recurring building types, could facilitate the transition toward a sustainable living model. Urban planning regulations play a decisive role in the success of self-sufficiency strategies. In some European regions, the recognition of standards for nearly zero-energy buildings has incentivized the redevelopment of the building stock, increasing the value of residential spaces and promoting sustainability on an urban scale. In Panzano, the adoption of local policies aimed at energy efficiency and sustainability could make the transformation of existing homes affordable, while simultaneously encouraging experimentation with new housing models that accommodate the fluid boundaries between different spatial experiences.

Beyond technical and regulatory aspects, the transition towards self-sufficient living implies a cultural and social transformation. The sharing of resources and knowledge can strengthen the sense of community and improve collective well-being, while addressing the contemporary conditions in which the boundaries of traditional typologies, between public and private, interior and exterior, are continuously redefined.

Approaching the case study of Panzano allows us to highlight how domestic self-sufficiency is not merely a technical issue but an interdisciplinary challenge involving architecture, technology, regulation, and society. The integration of greenhouse architecture as both a functional and spatial device demonstrates how contemporary dwelling can respond to the dissolution of traditional spatial limits while maintaining environmental performance. In comparison with other European contexts, it demonstrates that integrated strategies can improve energy efficiency, contribute to water and food autonomy, and enhance the value of existing building heritage, while accommodating the hybrid configurations that characterize contemporary living.

The adaptation of these models to the Panzano District represents not only an innovation but also an opportunity to promote a vision of sustainable and resilient living that embraces the ambiguity and flexibility required by contemporary patterns of mobility and climate adaptation. This approach, characterized by transparency, continuity, and functional hybridization, offers a replicable model for similar contexts facing the challenge of redefining dwelling in response to territorial transformation and changing lifestyle patterns.

Drawing from this context, the present study employs an integrated modeling approach to quantify the contribution of the proposed bioclimatic threshold-greenhouse system within the prevalent ‘H-type’ residential units of the Panzano District. This investigation is guided by a single core research question: To what extent does the integration of the threshold-greenhouse system contribute to the multidimensional self-sufficiency of these units, specifically considering the measurable enhancement of energy performance (passive and active gains), water autonomy (rainwater harvesting capacity for domestic and irrigation uses), and food resilience (potential yields from micro-horticultural cultivation)? The subsequent ‘Materials and Methods’ section will detail the specific scenarios (E-scenarios for energy and W-scenarios for water) and parameters used to evaluate these three dimensions.

Structure of the Paper

Section ‘Literature Review’ provides a scientific and cultural background on the implementation of bioclimatic greenhouses in the context of existing building heritage, with particular reference to multi-family residential buildings characterized by historical, cultural, and architectural values. The background outlines the features of bioclimatic greenhouses that can contribute to the self-sufficiency of the user unit, including: the improvement of the building’s energy performance and management;

increased efficiency in the use of water resources for domestic uses; and the potential for allocating resources to food production within the dwelling unit.

Section 'Materials and Methods' outlines the methodology adopted to assess the performance of a greenhouse in contributing to the energy performance of an existing building, by determining both direct and indirect contributions as well as thermal comfort conditions throughout different periods of the year. The section also describes the methodology for evaluating the volume of recoverable water that can be allocated for domestic use. Furthermore, the key parameters for assessing the bioclimatic greenhouse's contributions to user self-sufficiency within the identified thematic areas are defined. The methods and assumptions used to estimate the impact of solar spaces during the evaluation of the intervention's potential effectiveness are also detailed. In addition, the implementation of the methodology in the case study of the working-class district of Panzano is described, according to specific intervention scenarios. The selection of this case study is justified by the objectives related to energy efficiency, social revitalization, and the potential effectiveness of interventions on the existing building stock. The application of the proposed methodology enables an assessment of the impacts resulting from the integration of bioclimatic greenhouses into one of the prevalent building typologies within the Panzano District.

Section 'Discussion' highlights both the advantages and the critical issues associated with the implementation of these solar spaces within the context of significant housing pressure in the Panzano neighborhood. The analysis of the results is conducted in accordance with the scenarios outlined in the previous section, identifying possible configurations of the solar space and their respective impacts on the resources that contribute to the establishment of self-sufficiency within the existing urban fabric. Additional factors related to the nature and ownership of the building stock are also discussed.

Section 'Conclusions' summarizes the proposed approach for supporting self-sufficiency in historic and culturally significant building stocks, whose homogeneous nature allows for the potential replication of the intervention at a scale beyond that of the individual building. The limitations of the research conducted provide a basis for outlining future research developments.

Literature Review

The integration of sunspaces and bioclimatic greenhouses in existing building retrofits represents a multifaceted approach to addressing contemporary challenges in sustainable architecture.[1] The current state of research also addresses the incorporation of passive solar systems into residential building renovation projects, with particular emphasis on energy efficiency improvements, decarbonization potential, and impacts on occupant well-being and self-sufficiency, in relation to the EU's commitment to achieving carbon neutrality by 2050. The analysis reveals a growing body of evidence supporting the effectiveness of these interventions,

1. S. Brunoro, "Passive Envelope Measures for Improving Energy Efficiency in the Energy Retrofit of Buildings in Italy," *Buildings* 14, no. 7 (2024).

aligning with broader sustainability objectives while addressing the challenges of retrofitting existing residential stock.[2]

Research in Europe has made significant contributions to the field, particularly in the areas of architectural integration and climate-responsive design. Studies conducted in Mediterranean climates by Elaouzy and El Fadar provide comprehensive evaluation frameworks for bioclimatic design implementation, offering methodologies applicable across similar European climatic zones.[3] Northern European research has focused on cold climate applications, with significant contributions from Scandinavian researchers on thermal buffer zone concepts and high-performance glazing systems. The emphasis on heritage building integration and architectural sensitivity reflects European priorities in building renovation practices.[4] Southern European research has concentrated on cooling applications and thermal comfort optimization, with particular attention to passive cooling strategies and advanced glazing technologies aimed at overheating prevention.

Energy Performances and Thermal Effects

From a bioclimatic perspective, the threshold-greenhouse functions as a buffer space that shields the dwelling from adverse weather conditions during the colder seasons, while simultaneously acting as a passive solar system. The passive solar greenhouse represents an environmentally sustainable approach that, through its components and design, minimizes heat loss by capturing solar energy during the day and releasing it at night.

Recent research by Ma et al. provides a comprehensive review of sunspace applications in buildings, highlighting significant energy-saving potential.[5] Their analysis demonstrates that adding a south-facing sunspace to a cold-climate rural house significantly reduces January heating demand. This finding is corroborated by experimental studies conducted by Ma et al. in Qingdao, China, where a sunspace addition to an apartment building achieved substantial energy savings through passive solar gain and thermal buffering effects.[6] The thermal performance of sunspaces is heavily influenced by design parameters, as demonstrated by Vukadinović et al.[7] who investigated the impact of façade structure, glazing type, and window-to-wall ratio on energy performance. Their study revealed that optimized glazing configurations could improve thermal efficiency by up to 25%

2. R. Albatici, F. Passerini, and J. Pfafferott, "Energy Performance of Verandas in the Building Retrofit Process," *Energies* 9, no. 5 (2016).

3. Y. Elaouzy, and A. El Fadar, "A Multi-Level Evaluation of Bioclimatic Design in Mediterranean Climates," *Sustainable Energy Technologies and Assessments* 52 (2022).

4. G. Allesina, C. Ferrari, A. Muscio, and S. Pedrazzi, "Easy-to-Implement Ventilated Sunspace for Energy Retrofit of Condominium Buildings with Balconies," *Renewable Energy* 141 (2019): 541-548.

5. Q. Ma, X. Chen, X. Wang, W. Gao, X. Wei, and H. Fukuda, "A Review of the Application of Sunspaces in Buildings," *Energy Sources*, Part A 47, no. 1 (2021): 10292-10314.

6. Q. Ma, C. Xu, X. Chen, W. Gao, and X. Wei, "Experimental and Simulation Research on the Energy-Saving Potential of a Sunspace: An Apartment in Qingdao," *Sustainability* 15, no. 1 (2023).

7. A. Vukadinović, J. Radosavljević, A. Signorđević, and M. Protić, "Influence of Façade Structure, Glazing Type, and Window-to-Wall Ratio on Energy Performance," *Journal of Energy Engineering* 149, no. 1 (2023).

compared to conventional designs. Similarly, the integration of Phase Change Materials (PCMs) in sunspace systems has shown promising results.[8] Advanced thermal storage solutions have been explored by Afshari et al. who investigated solar energy storage in black-covered sunspaces using water-filled containers.[9] Their experimental and numerical study demonstrated effective thermal mass integration, providing stable indoor temperatures and reduced energy consumption fluctuations.

The evolution toward bioclimatic greenhouse systems represents a significant advancement in the field. Lotfinejad et al. developed a computational approach for integrating greenhouses with traditional architectural elements, utilizing genetic optimization algorithms to enhance thermal comfort while maintaining cultural and architectural integrity.[10] This approach demonstrates the potential for the sensitive integration of modern bioclimatic systems with existing building fabric, emphasizing architectural integration. The concept of thermal buffer spaces has gained prominence in cold climate applications. Yao et al. investigated the application of thermal buffer spaces in rural dwelling renovation for nearly zero energy consumption in cold regions of China, demonstrating the versatility of sunspace concepts across different climatic contexts and building types.[11]

Impact on Well-being and Quality of Life

A growing recognition of sunspace and greenhouse systems' contribution to occupant well-being beyond energy performance has emerged. Mazzeo et al. specifically addressed plant well-being in solar greenhouses, examining climatic conditions, glass selection, and environmental quality factors that influence both plant growth and human comfort.[12] Their research establishes important connections between agricultural productivity and human psychological well-being in integrated greenhouse-residential systems. Rong et al. investigated renovation strategies for green spaces in aging residential communities, emphasizing the dual benefits of carbon sequestration and wellness enhancement, thus contributing to community health outcomes while addressing environmental objectives.[13] The psychological and social benefits of integrated greenhouse systems are increasingly recognized in the literature, though this aspect remains underexplored compared to purely technical performance metrics. The presence of growing plants and natural systems

8. M. Ç. Uludaş, E. Tunçbilek, Ç. Yıldız, M. Arıcı, D. Li, and M. Krajčík, "PCM-Enhanced Sunspace for Energy Efficiency and CO_2 Mitigation," *Journal of Building Engineering* 57 (2022).

9. F. Afshari, E. Mandev, B. Muratçobanoğlu, A. Çelik, and M. A. Ceviz, "Experimental and Numerical Study on Solar Energy Storage in Black-Covered Sunspace Using Water-Filled Tin Cans," *Journal of Enhanced Heat Transfer* 31, no. 3 (2023): 21-44.

10. P. Lotfinejad, A. Tarkashvand, and H. Sanaieian, "A Computational Approach for Integration of Greenhouse and Shanashir to Enhance Thermal Comfort Using the NSGA-II Algorithm," *Building and Environment* 273 (2025).

11. G. Yao, X. Guo, Z. Qian, Y. Pang, Y. Zhang, and C. Xie, "Thermal Buffer Spaces in the Renovation of Rural Dwellings in Cold Regions of China," *Journal of Building Engineering* 99 (2025).

12. D. Mazzeo, C. Baglivo, S. Panico, and P. M. Congedo. "Solar Greenhouses: Climates, Glass Selection, and Plant Well-Being," *Solar Energy* 230 (2021): 222-241.

13. X. Rong, H. Fang, and C. He, "Renovation Strategies for Green Spaces in Aging Residential Communities in Cold Regions," *Buildings* 15, no. 8 (2025).

within or adjacent to living spaces contributes to improved mental health, stress reduction, and connection with natural processes.

Self-Sufficiency in Food and Water Production

The integration of food production capabilities in residential building retrofits represents an emerging frontier with limited but growing research attention. Yeo et al. conducted a detailed analysis of building-integrated rooftop greenhouses for urban agriculture, examining thermal energy loads and optimization strategies for combined residential and agricultural functions.[14] Current research indicates that properly designed building-integrated greenhouse systems can contribute significantly to household food security. Studies suggest that a well-managed residential greenhouse system can provide between 20-40% of a household's fresh vegetable needs, depending on system size, crop selection, and management practices.[15] Water self-sufficiency aspects are less extensively documented in the current literature: the potential for rainwater harvesting, greywater recycling, and the integration of hydroponic systems represent significant opportunities for future research.

The Sunspace as a Spatial Device

The architectural threshold is defined as a transition between two fixed states in cultural terms or between two dissimilar spaces in architectural terms. The concept of liminal space—from the Latin *limen*, meaning threshold—refers to a zone of transition between one's current position and one's intended destination.[16] In architecture, liminal entities—threshold spaces—are primarily characterized by their 'in-between' nature, situated between what they connect or separate, even though, in most cases, they constitute distinct and autonomous entities.

Liminal space is defined by features such as layering, dissolution, blurring, and ambiguity, and it possesses the capacity to 'transform' the occupant as they move through it. These transitional spaces are particularly relevant in contemporary domestic architecture, positioned between clearly defined functional areas, offering subtle and flexible connections within the spatial layout.

The threshold space thus emerges as a fundamental design device for mediating between opposing needs—privacy and connection, protection and openness, intimacy and sociability. Accordingly, the greenhouse is configured as a paradigmatic model of transitional space, capable of addressing the challenges of climate change through passive environmental control strategies, while simultaneously redefining the spatial and perceptual relationships between interior and exterior environments.

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14. U.-H. Yeo, S.-Y. Lee, S.-J. Park, J.-G. Kim, J.-H. Cho, C. Decano-Valentin, R.-W. Kim, and I.-B. Lee, "Rooftop Greenhouse: Thermal Energy Loads of a Building-Integrated Rooftop Greenhouse," *Agriculture* 12, no. 6 (2022).

15. J. Langemeyer, C. Madrid-Lopez, A. Mendoza Beltran, and G. Villalba Mendez, "Urban Agriculture—A Necessary Pathway toward Urban Resilience and Global Sustainability?" *Landscape and Urban Planning* 210 (2021).

16. V. Turner, *The Forest of Symbols: Aspects of Ndembu Ritual* (Ithaca, NY: Cornell University Press, 1970).

The Evolution of Greenhouse-Building Relationships: From Addition to Integration

The relationship between greenhouse and building has evolved significantly over the past decades, transforming from a simple functional addition to a sophisticated architectural device that challenges traditional boundaries between interior and exterior spaces. This evolution can be traced through four distinct phases, each representing a different approach to the integration of greenhouse technology with residential architecture.

The Greenhouse as Transparent Extension

The first phase represents the greenhouse in its most elemental form: a transparent architectural extension that preserves the distinction between the original building and the new addition.

Rick Mather Architects' Glass House in Hampstead exemplifies this approach, where innovation lies primarily in technical excellence rather than in spatial hybridization.[17] The project demonstrates how contemporary glazing technology can create a completely transparent structure through frameless double-glazed panels supported by laminated glass beams and columns (see Figure 1). A novel system with an invisible conductive film enables heat reflection and electrical conduction, providing radiant heating in winter and reducing solar gain in summer. This transformation allows the greenhouse into a year-round livable space. The intervention thus functions as both a climatic device and a spatial extension, maintaining a clear hierarchy in which the historic structure prevails and the glass addition acts as a technologically refined yet subordinate counterpart.

17. T. Dodd, *Rick Mather Architects: All Glass Extension and House Refurbishment, Hampstead* (2025).

Figure 1. *Architect Rick Mather's Glass Addition to a Georgian Cottage in Hampstead, London (1991/1992), North Facing Elevation (A Transparent addition that extends the living space while maintaining a clear distinction between the original building and the new intervention)*
Source: Dodd 2025.

Bioclimatic Integration

The second phase introduces a more integrated and environmentally responsive conception of the greenhouse. ACC Naturale Architettura's bioclimatic greenhouse in Superga exemplifies this evolution, framing the structure as an environmental mediator in dialogue with both architectural heritage and the landscape context[18].

Inserted within an early 20th-century building on the hill of Villa Sassi Park, the 50 m³ intervention demonstrates how form and orientation can be calibrated for energy efficiency and contextual harmony (see Figure 2). The polygonal plan reconciles solar exposure with the geometric constraints of the existing structure, while the aluminum frames with thermal break, double glazing, and titanium-zinc cladding with pre-patinated lichen-green pigment ensure both technical performance and visual integration. In this phase, the greenhouse transcends its role as an addition to become a bioclimatic device that actively mediates energy exchange and enhances the building's environmental performance.

18. C. Catino, *Capturing Bioclimatic Greenhouse, Superga* (Turin: 2021).

Figure 2. *ACC Naturale Architettura Cristiana Catino, in Superga, Turin (The greenhouse operates as an environmental mediator that harmonizes with both existing architecture and landscape context)*
Source: Catino 2021.

Symbiotic Equivalence

The third phase marks a paradigm shift in which the greenhouse attains architectural equivalence with the dwelling itself. In Lacaton & Vassal's Casa Latapie (Floirac, 1993),[19] industrial greenhouse components become the project's primary structural and spatial elements rather than ancillary additions[1, 2] (Lacaton & Vassal, 2008).[20] The east-facing greenhouse functions as a fully livable extension, its operable façades enabling seasonal adaptability and the modulation of light, intimacy, and ventilation (see Figure 3). This variability allows the domestic space to expand and contract, transforming from a minimal core to an open continuum that merges with the garden in summer. Through the use of inexpensive industrial materials and adaptable structures, the project redefines the dwelling as a flexible, responsive system. The greenhouse thus ceases to be a climatic accessory, becoming instead a generative framework for inhabitation – a co-dependent, symbiotic architecture in which both components share equal status.

19. Lacaton, A., and J.-P. Vassal. "Maison Latapie," in *El Croquis Omnibus: Lacaton & Vassal 1993–2015*, vols. 177-178, Madrid: El Croquis (2017): 48-57.

20. Lacaton, A. And J.-P. Vassal. "Maison Latapie, Floirac" (2008). https://www.lacatonvassal.com/index.php?idp=25 [Accessed 23 Jun 2025].

Figure 3. *Lacaton & Vassal's Casa Latapie in Floirac (1993) (The Greenhouse is no longer subordinated to the building but becomes an equivalent architectural component that shapes the entire dwelling concept)*
Source: Hisao Suzuki, in Lacaton & Vassal 2017.

Greenhouse Primacy

The fourth phase culminates in a complete inversion of the traditional hierarchy, as the greenhouse becomes the primary architectural envelope encompassing the dwelling. In Niederwöhrmeier + Kief's residential project in Nuremberg (2000), the 'house within a greenhouse' typology redefines the relationship between structure and enclosure (Niederwöhrmeier + Kief, 2016). Here, the transparent shell forms the dominant climatic and spatial framework, while the enclosed living units are conceived as inserted volumes within a larger, environmentally controlled space (see Figure 4).

Figure 4. *Niederwöhrmeier + Kief's residential project in Nuremberg (2000) (The greenhouse envelope becomes the primary architectural element that encapsulates and protects the dwelling within)*
Source: Niederwöhrmeier + Kief 2016.

This layered system of boundaries mediates between interior and exterior, optimizing comfort and adaptability. The project exemplifies the greenhouse's evolution from an ancillary addition to an autonomous architectural organism – one in which environmental regulation and transparency become the central generative principles of domestic architecture.

Toward Hybrid Domesticity

This evolutionary trajectory reveals how the greenhouse has transformed from a simple functional addition to a sophisticated architectural device capable of redefining domestic space. Each phase represents not merely a different approach to greenhouse integration, but a different understanding of the relationship between building and environment, between interior and exterior, between protection and exposure. The progression from addition to integration, to symbiosis, and finally to encapsulation demonstrates how contemporary architecture is moving toward increasingly fluid and responsive relationships between built form and environmental systems. The greenhouse, in its various configurations, becomes a testing ground for new forms of domesticity that can respond to changing climate conditions, lifestyle patterns, and spatial needs.

This evolution suggests that the future of domestic architecture lies not in fixed relationships between building components, but in dynamic systems that can adapt and transform according to varying environmental and functional requirements. The greenhouse, as both a technical device and a spatial concept, offers a model for this new architecture of adaptability and environmental responsiveness.

Materials and Methods

This study represents a practical continuation within the broader research framework developed under the INEST – Interconnected Nord-Est Innovation Ecosystem project, funded by the European Union and the Italian Ministry of University and Research as part of the investments envisaged by the National Recovery and Resilience Plan.[21] Specifically, it focuses on strategies for the sustainable regeneration of the existing building stock.

The projects evaluated in the first phase of this research are characterized by modified façade components and transitional architectural elements, designed to adapt dwellings to emerging needs, expand usable space, and reduce environmental impact, thus resulting in new envelope configurations.[22] In addressing the challenges of energy footprint reduction and climate adaptation, technology becomes a key

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21. E. Zatta, M. Condotta, R. Revellini, and V. Tatano, "Delivering Sustainability in the Italian N-E Built Environment," *Buildings* 13, no. 12 (2023).

22. P. Limoncin, T. Bisiani, and C. A. Stival, "Façade Additive Strategies to Foster a Wider Concept of Comfort," in *Proceedings of the 4th International Conference on Sustainable Development in Civil, Urban and Transportation Engineering* (ed.) A. Różański et al., 177-187 (Singapore: Springer Nature, 2025).

element of the architectural design process, enabling more effective strategies for retrofitting.

However, beyond technical solutions, it is equally crucial to consider interventions that enhance spatial quality through the reciprocity between people and their environment. In this context, the architectural threshold—understood as a liminal space of transition—offers a powerful design tool. Elements such as passive solar greenhouses exemplify this potential: they serve not only as environmental buffers that improve energy performance, but also as redefined domestic spaces that mediate between interior and exterior, fostering inclusive and transformative spatial experiences.[23]

Sunspace Integration within an Existing Layout

The greenhouse, understood as an architectural threshold device, offers an innovative model for reimagining the domestic entrance in the era of climate change. Through its capacity to mediate between different environmental conditions and to create ambiguous and flexible transitional spaces, the greenhouse represents a design strategy that responds to the evolving needs of contemporary living, increasingly defined by mobility, adaptability, and climate responsiveness.

The design hypothesis outlined here proposes the greenhouse as an architectural device that synthesizes the spatial characteristics of the threshold with the specific environmental and bioclimatic qualities of the glazed structure. This synthesis does not result from a mere juxtaposition of elements, but rather from the generation of a new spatial category, creating an innovative and functional configuration that bridges two traditionally distinct architectural domains.

Moreover, the integration of food production systems within residential building retrofits represents an emerging area of research that is receiving increasing scholarly attention, particularly in the context of urban resilience, self-sufficiency, and the circular economy. The incorporation of productive greenhouses into the domestic realm contributes to environmental performance but also to social and spatial innovation, enhancing the dwelling's capacity to support sustainable lifestyles.

Modelling a Greenhouse

The general objective is to evaluate the potential contribution of the bioclimatic greenhouse and its integrated system in generating three forms of self-sufficiency:

- Energy self-sufficiency, through the reduction of primary energy demand for heating and cooling, due to the seasonal buffer effect of the greenhouse.
- Water self-sufficiency, through the recovery and reuse of rainwater.
- Food self-sufficiency, in terms of supporting domestic micro-horticultural production.

23. C. A. Stival, T. Bisiani, and P. Limoncin, "Criteria for Enhancing Comfort and Liveability through Innovative Façade Interventions," *Architecture, Structures and Construction* 5, no. 1 (2025): 14.

The adopted methodology is based on an integrated approach combining energy and water simulation, initially conducted through the construction of a parametric model in a BIM (Building Information Modeling) environment and supported by a calculation code for evaluating specific contributions in terms of energy and stormwater management.

In the assessment of energy self-sufficiency, the model aims to define the greenhouse contributions on a monthly basis, considering three main scenarios codified with letter 'E':

- Current state "E0", which represents the actual condition of the building, without any intervention;
- Project state "E1", which involves the addition of bioclimatic solar spaces as an integrated architectural extension, positioned on the building façades to promote appropriate passive contributions to the building's useful energy balance;
- Project state "E2", which includes, in addition to the greenhouse, the installation of photovoltaic panels on top of the new bioclimatic solar space, with the objective of introducing energy self-production.

Regarding the introduction of a system for direct use and recovery of stormwater, three possible scenarios – identified with letter "W" – are defined:

- Current state "W0", representing the actual condition of the building with no rainwater recovery; Project state "W1", which considers the collection of meteorological water draining over the new volume of the bioclimatic solar space for indoor irrigation purposes;
- Project state "W2", which considers the collection of meteorological water draining over the new volume of the bioclimatic solar space for indoor and garden irrigation purposes;
- Project state "W3", which considers the collection of meteorological water for both irrigation and domestic uses.

Parameters for Energy Modeling

The energy model, based on monthly calculations, is developed in compliance with ministerial decrees implementing Directive 2023/1791/EU and the technical standards cited to standardize the calculation method (UNI/TS 11300 standard series). The building energy model considers, as significant outputs, the useful thermal energy demand and the primary energy demand: the former is essential for evaluating, in different scenarios, the contribution of the bioclimatic greenhouse to the building's net energy performance; the latter is evaluated to define the contribution of the photovoltaic surface to the same performance.

The model for evaluating the contribution of the bioclimatic greenhouse, in particular, employs the following parameters:

- Climatic data of the location, expressed on a monthly basis: solar radiation on different exposures, mean outdoor air temperature, and outdoor air relative humidity.
- Geometric parameters of the greenhouse: useful surface area and useful volume of the space, surface area of transparent and opaque technical elements facing the outdoor environment, surface area of transparent and opaque technical elements facing the indoor environment (i.e., the existing building).
- Material parameters of the greenhouse: thermal transmittance and solar factor of transparent surfaces, thermal transmittance and thermal capacity of opaque surfaces, both facing outdoors and at the interface with the existing building.
- Thermal exchange parameters for ventilation, between greenhouse and outdoor environment, and between the indoor environment and the greenhouse.

Parameters for Hydrologic Modeling

For the assessment of the contribution related to sustainable water resource management, a daily per capita consumption of 130 liters is assumed for a dwelling within a multi-ownership residential building.[24] This overall value considers both services requiring potable water (personal use, surface cleaning, food production and cooking) and services for which such a water quality level would not be necessary (toilet flush, outdoor irrigation, use of household appliances).

The estimation of the water volume available monthly through precipitation is evaluated according to the following parameters:

- Climatic data of the site: cumulative precipitation per month.
- Geometric and finishing parameters of the greenhouse and existing building: greenhouse roof surface area, existing roof surface area involved in rainwater collection, runoff coefficients of collection surfaces.
- Geometric parameters of dwellings: useful surfaces and volumes, number of users per dwelling, external surface area designated for gardening, surface area designated for greenhouse cultivation.
- Parameters necessary to define the balance between collected water volume and that subject to evapotranspiration phenomena: vegetation water requirements, heat island effect on vegetation, vegetation density, depending on the specific plant species.

The building hydrologic model considers, as consistent outputs, the rainwater harvesting volume made available for irrigation purposes and domestic uses. Moreover, the model allows for the implementation of the effect of a dual system for the collection, storage, and reuse of rainwater, which allocates the stored volume to specific uses for which water quality equivalent to potable water is not required.

24. S. Donatello, M. Cordella, and N. Dodd, *Use-Stage Water Consumption*, 2021.

The YAS (Yield After Spillage) method is employed, which is one of the internationally adopted standards for water resource assessment.[25]

A Remarkable Context for Application: The Panzano District in Monfalcone

The working-class district of Panzano, developed in close relationship with the Monfalcone Shipyard at the northernmost coast of the Adriatic Sea, constitutes an architectural and urban heritage of significant historical and cultural value (see Figure 5).

The industrial settlement – initiated in 1908 by the Cosulich Navigation Company – was conceived as a 'garden city' combining efficiency, hygiene, and technical rationality, providing housing for about 5,000 inhabitants and functioning as an autonomous urban nucleus alongside Monfalcone.[26]

Its development unfolded in three phases: initial spontaneous workers' housing (until 1913), a more structured plan before World War I, and the major expansion between the post-war period and 1927, which completed the residential areas and public facilities. The result was a coherent integration of productive and residential functions, articulated through a hierarchy of dwellings – ranging from modest workers' houses to larger managerial residences (with areas ranging from 40 to 400 m^2) – organized according to social and professional roles.[27]

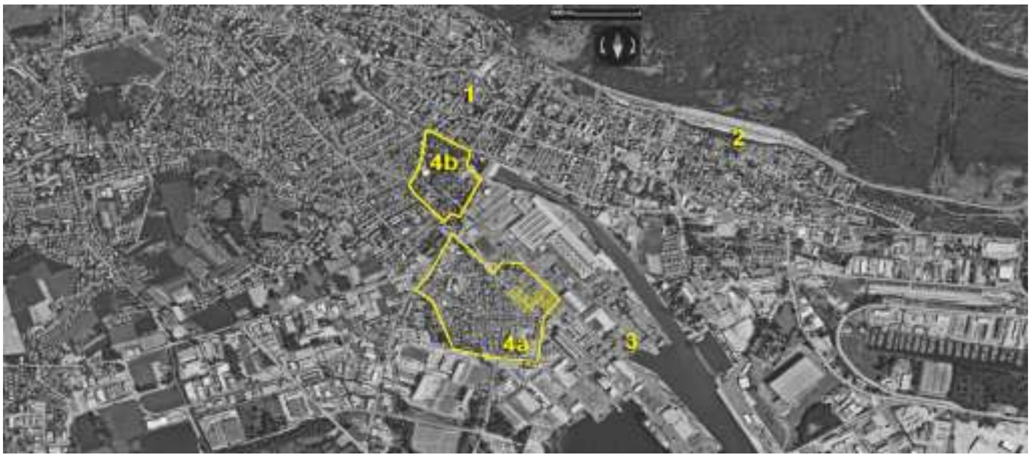

Figure 5. *Location of the Panzano District in Monfalcone: 1) Monfalcone City Center; 2) Railway Station; 3) Naval Shipyard Area; 4a) District Workers' Village; 4b) Employees' and Managers' Houses*
Source: Authors elaboration on current satellite view from Google Maps®.

After World War II, the paternalistic model underpinning Panzano declined, leading to social fragmentation and architectural decay due to the shipyard's

25. N. S. Muhammad, and M. W. Lin. "Reliability of Rainwater Harvesting Systems Using the Yield-After-Spillage Algorithm," In *Proceedings of the AWAM International Conference on Civil Engineering*, 481-494 (2022).

26. Project Group of Panzano Municipality for the Panzano Recovery Plan, *Panzano Recovery Plan: General Report* (Monfalcone, 2010).

27. E. Valcovich, and F. Gadaleta, *Catalogo Panzano 1950–2017* (Monfalcone: Comune di Monfalcone, 2017).

disengagement and the lack of coordinated maintenance.[28] Starting in the 1980s, municipal initiatives sought to counter this degradation through a Recovery Plan (1987) and later regional funding (1995) for the preservation of the district's typological features. The Neighborhood Contract launched in 1995 introduced experimental interventions aligned with bio-architecture, energy efficiency, and accessibility principles, aimed at maintaining residents' permanence and restoring social cohesion.[29]

Successive, uncoordinated interventions, however, generated typological heterogeneity, fragmenting the original architectural unity. The 2010 Recovery Plan sought to address these issues by preserving the existing building heritage and regulating building additions – both volumetric (extensions, verandas, garages) and non-volumetric (canopies, pergolas) – to safeguard the district's morphological identity. Architecturally, Panzano remains characterized by diverse housing types, recalling the urbanized countryside model through low-density layouts, individual garden plots, and dwellings designed for potential extensions. These features now offer the potential to reinterpret the workers' village through contemporary notions of comfort, adaptability, and environmental quality.

The 'H-type' Building as a Case Study for Sunspace Integration

Among the various typologies present in the neighborhood, the so-called "building type 1A" or "H-type" deserves particular attention. This consists of articulated block buildings comprising eight dwellings of approximately 54 m2 each, distributed across two levels (four per floor) of 3.00 meters gross height; independent access points and small plots of land are assigned to each unit. In total, 18 buildings of this type were constructed, comprising a complex of 144 dwellings (see Figure 6).

28. D. Barillari, and C. A. Stival, "The Industrial Heritage of the Trieste Shipyard in Monfalcone: Restoring the Garden-City Model in the Residential Typologies of the Panzano District," *Journal of Architectural Conservation* 28, no. 3 (2022): 217-242.

29. Project Group of Panzano Municipality for the Panzano Recovery Plan, *Panzano Recovery Plan: General Report*, 2010.

Figure 6. *Situation Plan (2010) of the Building Stock Typologies in the Workers' Village: The Continuous Red Line Borders the Perimeter of the Recovery Plan Scope. In the Key Legend, Codes 1A and 1B Refer to Eight-dwelling Houses with Separate Entrance, which Constitute the Focus of this Study*
Source: Project Group of Panzano Municipality for Panzano Recovery Plan, 2010a.

This typology, initially introduced before the Second World War and reintroduced in 1920-1921, represents the oldest and most widespread residential type in the neighborhood. Each dwelling, directly connected to its own plot, comprises a kitchen, two bedrooms, a bathroom, and circulation spaces, and is completed by a basement level (see Figure 7).

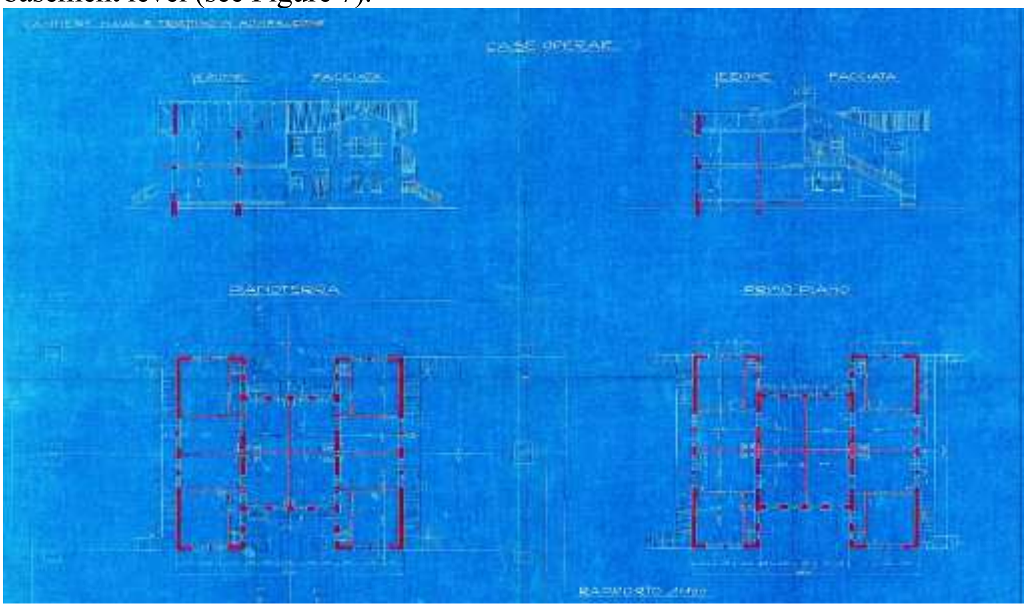

Figure 7. *Drawing for the 'H-type' Housing Project, Typology 1A. Crossed Sections, Main and Lateral Fronts, Ground Floor and First Floor*
Source: Barillari & Stival, 2022, courtesy of Monfalcone Municipality Historical Archive.

The load-bearing structure is constructed with brick masonry on reinforced concrete foundations, while the floors and roof are timber-framed. The building exhibits elements characteristic of rural architecture, such as the deeply projecting roof and external staircases with access balconies to the first floor. Overall, the articulation of entrances and the morphology of the roofing systems remain consistent with the original architectural language.

Over time, numerous uncoordinated interventions—particularly the construction of verandas to protect entrances—have generated a widespread phenomenon of superimposition, partially altering the original typological configuration in several building typologies in the District (see Figures 8-9).

Figure 8. *Views of the 'H-type' Housing in the Workers' Village of Panzano (Recent additions are visible on the ground floor and above the balcony, protecting entrances to dwellings)*
Source: Authors 2023.

Figure 9. *Existing Additions Providing Entrance Protection across Different Building Typologies in Panzano District: The Adopted Protective Systems Vary in both Type and Style*
Source: Authors 2023.

However, these conditions represent an opportunity to redefine the spatial configuration and technical performance of the buildings, updating them according to contemporary concepts of residential well-being. This can be achieved through the insertion of an additional and integrated architectural element capable of introducing self-sufficiency functions to a housing stock currently lacking them. From this perspective, the integration of a bioclimatic solar greenhouse within the eight-dwelling typology represents the focal point of the design proposal. The greenhouse space, conceived as an openable winter garden, is aimed at improving energy performance and achieving forms of self-sufficiency, including water and food production. International experiences confirm the validity of integrating passive-active devices in historic residential contexts, capable of ensuring energy autonomy and comfort while respecting the pre-existing architectural identity.

The analysis focused on residential typology "1A", previously subjected to examination for the identification of preliminary design solutions aimed at enhancing the quality of living spaces. By applying transitional façade systems within the building stock of Northeastern Italy, the research highlights both the architectural adaptability of this typology and the evolution of research methodologies developed within the INEST project. This approach exemplifies how climate-responsive and spatially inclusive strategies can be effectively embedded into broader design frameworks for contemporary retrofitting, beyond issues related to sustainable regeneration.

Characterization of Sunspace Integration on 'H-type' Building

The application of the bioclimatic solar greenhouse to the building typology under investigation involves the integration of new spaces within the setback areas provided by the building volume; consequently, two new volumes are defined with

South-West and North-East orientations. This solution encompasses all the eight dwelling units present in the 'H-type'. The two hypothesized greenhouses are thus configured as double-level volumes, each of which is subdivided into four spaces pertaining to each dwelling unit. Given that access to the dwelling units is independent and occurs within the building setbacks only for ground-floor units (upper-floor units are accessible via balconies), the greenhouse assumes different functions at the two levels. Moreover, the sunspace volume works as a buffer space for North-East orientation, while the sunspace facing South-West works effectively as a passive solar system (see Table 1 and Figures 10-11).

Table 1. *Relevant Climatic Data for the Study of a Solar Greenhouse in Monfalcone*

Month	Outdoor air Temperature [°C]	Average NE Solar Radiation [MJ m^{-2}]	Average SO Solar Radiation [MJ m^{-2}]	Average Horizontal Solar Radiation [MJ m^{-2}]
January	3.4	1.56	6.89	4.40
February	5.4	2.89	8.83	7.30
March	9.2	5.19	11.20	11.80
April	12.9	7.53	11.22	15.20
May	18.5	10.40	11.88	19.30
June	22.2	12.90	13.28	23.50
July	23.5	11.89	12.73	21.70
August	23.1	9.50	12.39	18.40
September	19.3	6.72	11.77	14.20
October	14.6	3.78	9.23	8.80
November	8.7	1.88	6.99	5.00
December	5.5	1.38	6.15	3.80

Source: regulation UNI 10349, parts 1 and 2, 2016.

The greenhouse envelope consists of double glazing with high solar transmittance (g=0.75) in order to balance solar gains during the cold season and thermal losses (U=2.80 W m-2 K-1), mounted on partially openable frames. The greenhouse envelope comprises an independent steel structure with uprights and crossbeams, equipped with its own foundations to avoid affecting the structural behavior of the existing building. The steel structure also allows for the extension of the intermediate floor slab (necessary for the use of the solar space on the upper floor), to be constructed in timber for consistency with the existing floor systems, and for the implementation of the upper closure of the greenhouse, consisting of double glazing with high solar transmittance (design scenario E1) or photovoltaic glazing with amorphous silicon (scenario E2).

The steel structure of the solar greenhouse allows for the integration of a rainwater collection downpipe within the central mullion, positioned at the division between the two floor-level dwelling units, to collect precipitation from the roof surface. The internal cross-section of the central mullion must be subdivided into four equal sectors by means of longitudinal dividing profiles, in order to distribute the rainwater flow made available for the intended uses in the W1-W2-W3 scenarios from the point of roof collection. This approach ensures uniform flow distribution to the utilities of the different dwelling units.

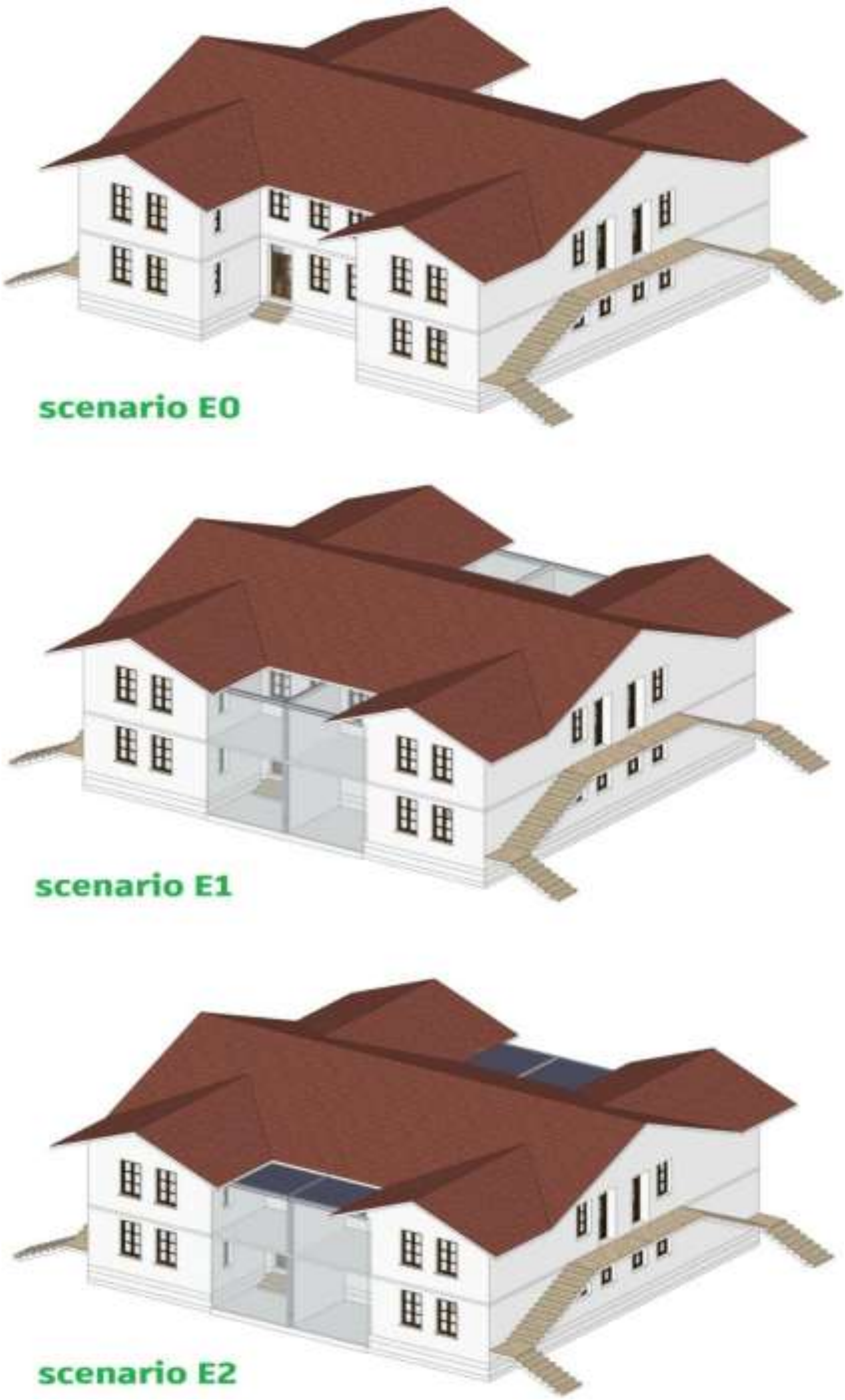

Figure 10. *BIM Model Comparing Scenarios for Different Energy Contributions in the Integration of Greenhouses in Building Type "1A" in Panzano District: From Top to Bottom, State of Fact, Greenhouse Integration, Greenhouse Integration with Solar Photo-voltaic Integration on Rooftop*
Source: Authors 2025.

The proposed interventions on building typology “1A” do not entail invasive effects on the structural behavior of the building type: the façade addition is indeed conceived to operate autonomously and to be potentially removed according to the principle of reversibility of the intervention. From a building services perspective, furthermore, the intervention does not modify the existing internal systems but is limited to introducing passive components with low impact, and active components for electrical energy production in the case of scenario E2.

The catchment surface at the top of each greenhouse, significant in terms of energy balance, in both scenarios E1 and E2 is 12.15 m2, as part of the greenhouse’s rooftop is covered by the ridge overhangs of the pitched wooden roof structure, which is characteristic of the original building. In the W1-W2-W3 scenarios, however, a meteorological water collection surface of 94.20 m2 is considered, as this also includes the surface of the existing roof whose slope channels rainwater toward the greenhouse roof. The runoff coefficients are assumed to be 0.80 for the existing roof, with roof tiles as covering, and 0.95 for the greenhouse roof, whose finishing consists of a glass panel.

The original opaque envelope of the building, which constitutes the thermal exchange surface with the greenhouse, features opaque technical elements in solid masonry with thermal transmittance of 1.40 W m^{-2} K^{-1}, and windows with thermal transmittance of 2.80 W m^{-2} K^{-1} that constitute 18% of the surface area of this envelope. Each greenhouse has a gross floor area of 48.40 m^2 distributed over two levels and four dwelling units: each unit therefore has an additional surface area of 12.10 m^2 designated as greenhouse space. The total volume of each greenhouse, equal to approximately 140 m^3, presents thermal storage surfaces determined by the extension of the intermediate horizontal partition and by two new vertical partitions separating the dwelling units having the same level and the same orientation; these technical elements provide a thermal capacity of 4.24 MJ K^{-1}.

To control overheating effects in the greenhouse, it is possible to apply external shading systems to the greenhouse itself, aimed at containing solar gains from April to October, reducing them to 25% during the summer period (June-August).

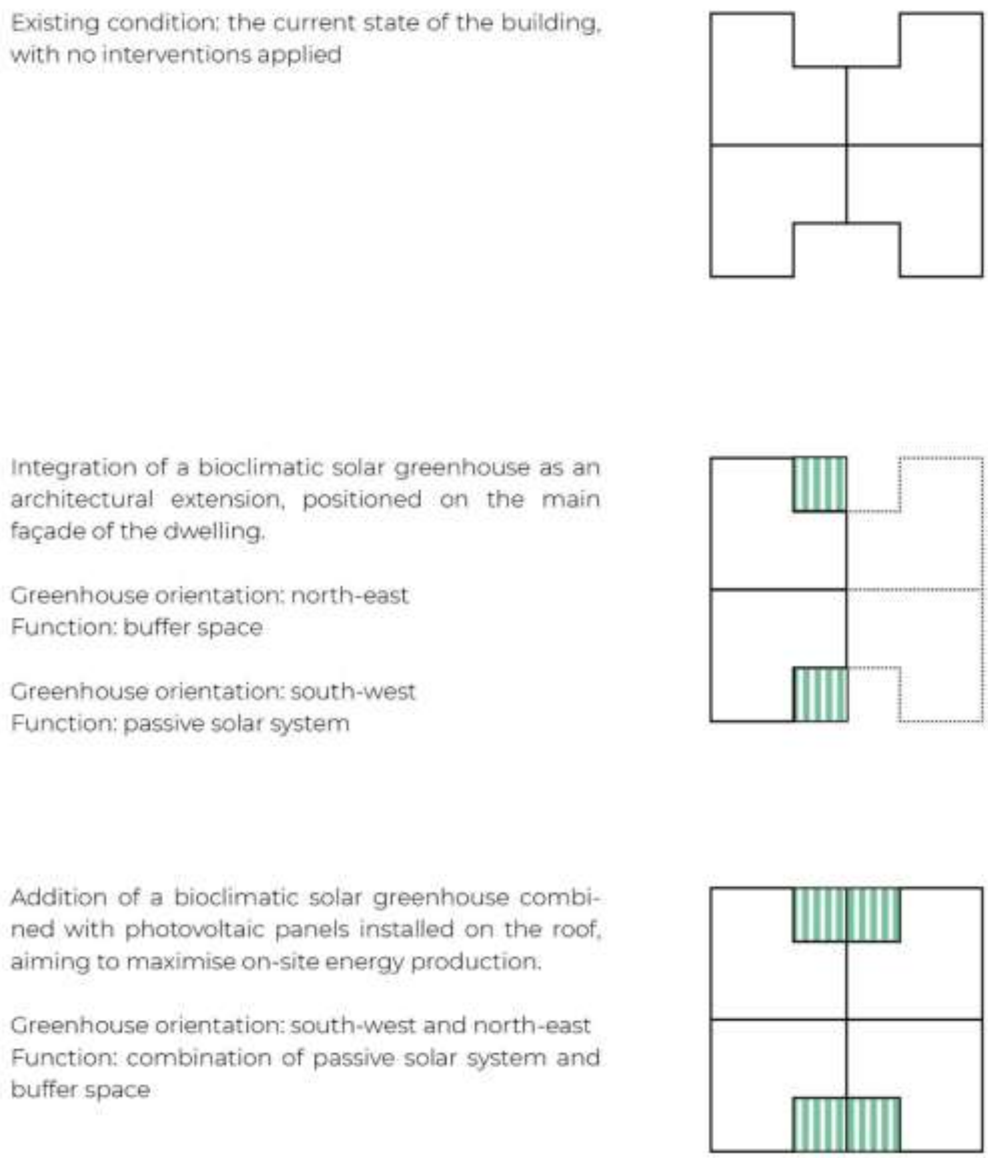

Figure 11. *Comparative Integration Scenarios for Building Type "1A" in Panzano District (The proposed interventions are intentionally non-invasive with respect to the original spatial and typological configuration, ensuring compatibility with the village's conservation constraints while promoting adaptive and incremental regeneration strategies)*
Source: Authors 2025.

With the same objective, differentiated ventilation regimes are applied throughout the year:

- the ventilation rate between the external environment and the greenhouse is assumed to be 0.5 vol h^{-1} during intermediate seasons, and reduced to 0.1 vol h^{-1} during the July-August and November-February periods;

- the ventilation rate between the greenhouse and internal environments is assumed to be 1.0 vol h^{-1} during the winter season, decreasing to 0.1 vol h^{-1} during the summer season.

The hypothesized cultivated area within the greenhouse is 1.75 m^2, a surface area that falls under the category of home-based gardening, recognized as a practice capable of contributing significantly to household food security.[30] This model enables the integration of the family diet with fresh, self-produced vegetables, reducing dependence on external supply sources and promoting greater urban resilience (see Figure 12).

Figure 12. *Comparative Diagram for Assessing the Potential Contribution of the Bioclimatic Greenhouse and the Integrated System in Supporting Three Forms of Self-sufficiency: i) Water, through Rainwater Harvesting and Reuse; ii) Energy, through the Reduction of Energy Demand for Heating and Cooling; Food, by Enabling Small-Scale Domestic Vegetable Production*
Source: Authors 2025.

In accordance with the W1-W2-W3 scenarios, the use of recovered rainwater can be designated exclusively for self-production purposes related to solar greenhouses (W1), or alternatively, additionally supplying toilet flush tanks intended for domestic use (W2). Both scenarios also consider the plot of land associated with each dwelling unit (75 m^2 each) and highlighted in the figure, thus recalling the original purpose that guided the conception and construction of the workers' village (see Figure 13).

Discussion

On the ground floor, the threshold-greenhouse functions as an introductory space to the dwelling, mediating the transition from the public or semi-public realm to the private domain of the individual housing unit. This transition does not occur through an abrupt separation, but rather through a gradual spatial sequence that accompanies the shift from collective behaviors to typically private actions. These transitional spaces are characterized by their capacity to facilitate social interactions between exterior and interior environments, creating opportunities for a range of intermediary activities.

30. A. L. Thebo, P. Drechsel, and E. F. Lambin, "Global Assessment of Urban and Peri-Urban Agriculture," *Environmental Research Letters* 9, no. 11 (2014).

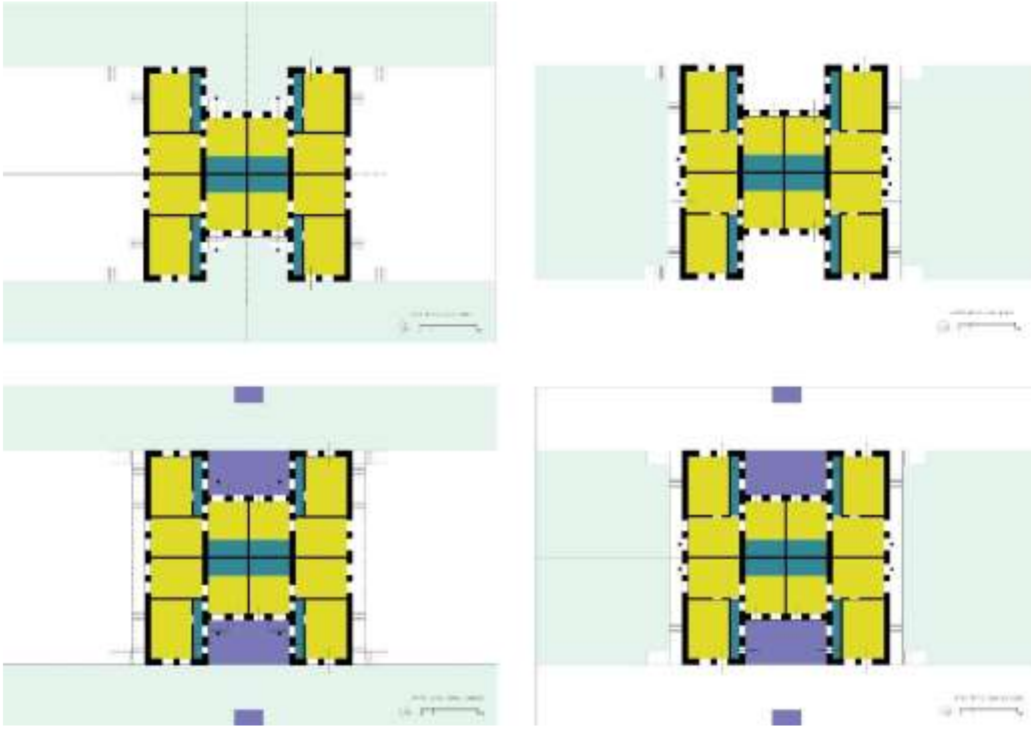

Figure 13. *Plans Identifying the Eight Dwellings—Four on the Ground Floor and Four on the Upper Floor—Across the Design Scenarios for Greenhouse Integration (Primary Spaces are shown in yellow, secondary spaces in blue, the corresponding plot in green and the integrated greenhouse in violet)*
Source: Authors 2025.

On the upper floor, the threshold-greenhouse provides a predominantly transparent space that extends the boundaries of the dwelling, generating a bright and comfortable environment that maintains a controlled connection with the exterior. This configuration challenges the traditional view of the greenhouse as a space solely dedicated to cultivation, transforming it into a versatile setting capable of accommodating various domestic functions.

The transparency of the glazed structure goes beyond ensuring visual continuity – it becomes a means of regulating both privacy and openness toward the outside. Transitional spaces can serve as buffer zones between private and public areas, contributing to passive thermal and acoustic regulation. Elements of environmental and visual control can be selectively calibrated to reinforce a sense of enclosure and protection, or conversely, to enhance the relationship with the urban context, in response to diverse usage needs and the temporal variations of domestic life.

The two solar greenhouses are capable of producing significant solar gains, according to the boundary conditions illustrated in the 'Materials and methods' section. As initially hypothesized, the southwest exposure proves more favorable and operates as a bioclimatic solar greenhouse; the northeast-exposed greenhouse is instead configured primarily as a buffer space protecting the residential spaces in continuous use (see Figure 14).

With reasonable assumptions regarding the shading of the transparent surface (particularly the southwest-facing façade, which experiences the highest solar load) and thermal exchange through ventilation between the outdoor environment and the greenhouse, and between the greenhouse and indoor environments, the temperature remains predominantly below 30°C during the summer season.

It should be emphasized that the southwest-exposed greenhouse exhibits a thermal situation such that it requires no additional mechanical thermal inputs throughout the entire year. The situation differs for the northeast-exposed greenhouse, where thermal exchange through transmission is very high during the winter season (see Figure 15).

The predictive assessment of PMV, according to the EN 7730 standard, demonstrates the acceptability of thermal comfort conditions for three months per year:

- During mid-winter for the southwest-exposed greenhouse.
- At the beginning and at the end of winter for the northeast-exposed greenhouse.

This outcome is consistent with the function of a solar greenhouse, which serves to collect solar radiation and assist in heating the building to which it provides access, ensuring a reduction in energy consumption. The bioclimatic greenhouse, given its essential function of complementing and providing energy savings to the building with which it is integrated, is a technical volume that cannot legitimately be designated for permanent human occupancy.

The impact of the two greenhouses on the overall building performance is significant. In scenario 'E1', a reduction of approximately 20% in thermal energy and primary energy requirements is achieved, in the absence of renewable sources intervening in energy generation; approximately 70% of this mitigating effect is attributable to the southwest-exposed greenhouse. In this case, it is therefore predictable that dwellings opening onto the southwest greenhouse are clearly advantaged compared to others.

Less impactful is the implementation of integrated photovoltaic roofing technology on the two greenhouses, which does not directly influence net thermal energy (a typical passive effect), but rather reduces non-renewable primary energy requirements by approximately 12%. The limited effect is due to the small surface dedicated to active energy production; the surface availability for a properly sized photovoltaic installation should consider the existing building rooftop, characterized by a 46% slope and, thus, capable of more efficient power production (see Figure 16).

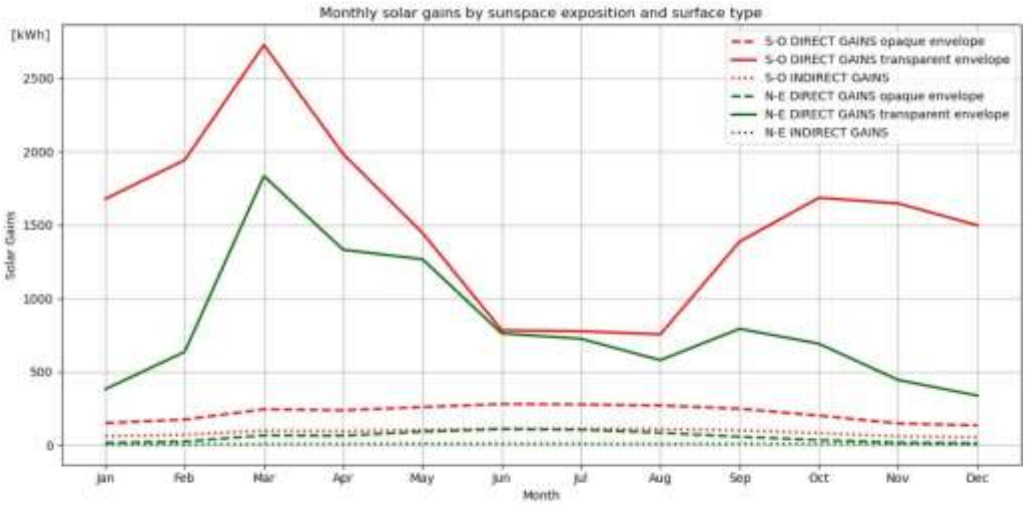

Figure 14. *Monthly Solar Gains Provided by the Sunspaces with S-O and N-E Expositions, in Red and Green Respectively*
Source: Authors 2025.

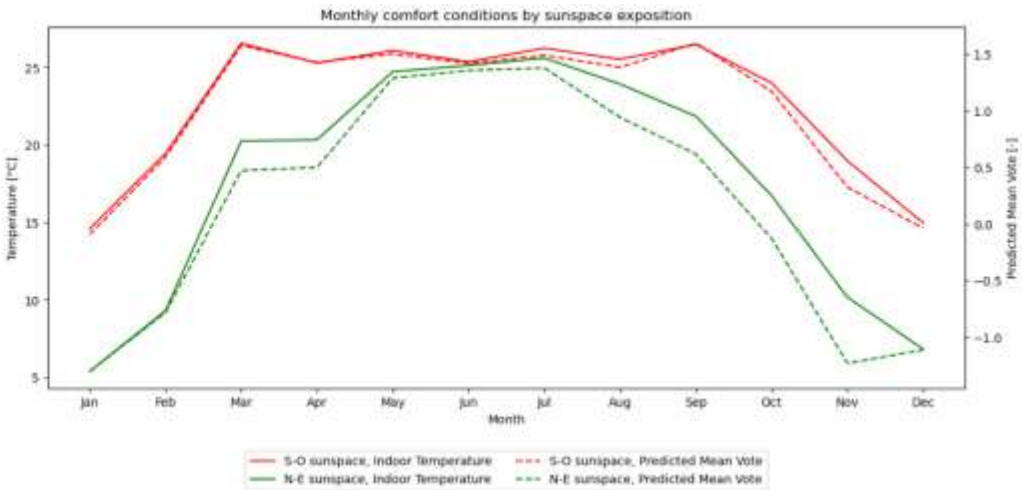

Figure 15. *Monthly Comfort Conditions within the Sunspaces with S-O and N-E Expositions, in Red and Green Respectively*
Source: Authors 2025.

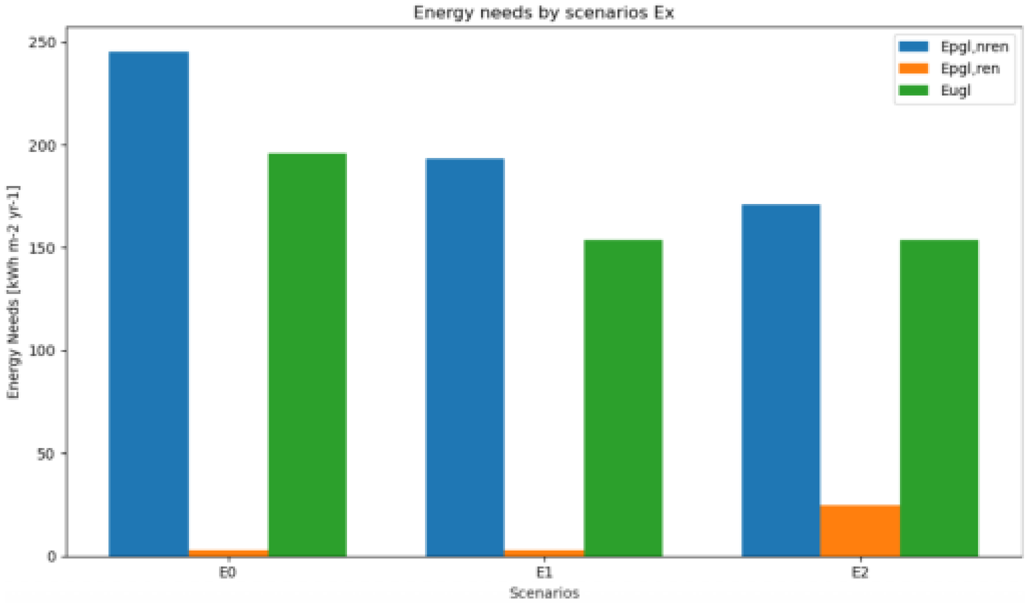

Figure 16. *Energy Needs of "1A" Building Typology according to Ex Scenarios: Non-renewable Primary Energy Performance (blue), Renewable Primary Energy Performance (orange), Net Energy Performance (green) (The indices are evaluated per surface unit and year)*
Source: Authors 2025.

The integration of a stormwater collection system in the solar greenhouse structure shows promising potential. When initially considering scenario W1, a temporal mismatch is evident between periods of highest precipitation (spring and late autumn) and periods of greatest water demand for plant species. Nevertheless, quantitative analysis demonstrates that the volume of collected rainwater is sufficient to satisfy the irrigation requirements of greenhouse crops for eight months; in the remaining months, during the June-September period, minimum coverage equals 30% (in August).

In scenario W2, which additionally considers garden irrigation, complete coverage decreases to six months per year, with minimum coverage slightly exceeding 3% during the three summer months. These minimum values are confirmed in scenario W3, where coverage exceeds 65% from October to March (see Figure 17).

The simulation analysis primarily evaluates the system configuration for the use of recovered rainwater. For scenarios W1 and W2, it is possible to consider a rainwater recovery system devoid of a storage volume, where the water resource is allocated primarily to greenhouse crops (through capillary or drip irrigation systems), and subsequently, for the excess, unused water volume, to the garden associated with each dwelling unit. This solution enables the subsequent design to focus on flow-rate control for cultivated species through an adequate sizing of components and water supply branches, avoiding the need for a dual system that would otherwise be required in scenario W3.

The results also allows us to evaluate approximately 4,000 liters the optimal volume for the potential storage tank of recovered rainwater, whose size is considered compatible with the dimensions of the dwellings and suitable for a non-invasive underground placement in the adjacent gardens.

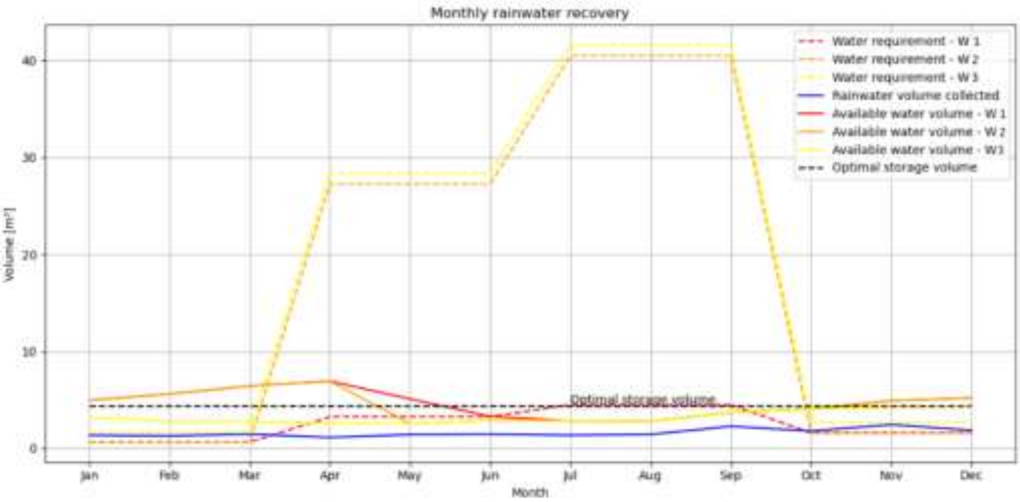

Figure 17. *Water Recovery and Reuse in "1A" Building Typology according to W1-W2-W3 Scenarios (Dashed lines represent the water requirement for uses associated to each scenario; continuous lines the water volume made available month by month that allow to individuate the optimal storage volume)*
Source: Authors 2025.

The environmental parameters of the solar greenhouse present several advantages for intensive cultivation. The internal temperature remains within an optimal range for most horticultural crops throughout the year, never falling below 18°C nor exceeding 34°C. Such stability supports year-round production and eliminates the need for active heating or cooling systems. Water availability is derived entirely from a rainwater harvesting system, with a minimum of 1,500 liters/month reliably accessible and peak availability reaching up to 3,500 liters/month. Estimated irrigation needs for the 1.75 m^2 cultivation area vary seasonally, ranging from approximately 20 liters/day during winter to a maximum of 150 liters/day (or 4,500 liters/month) during peak summer. This means that, while water sufficiency is guaranteed during most of the year, summer conditions might exceed the collection capacity, necessitating either water-saving strategies (e.g., mulching, drip irrigation, cultivar selection) or reduced production intensity.

Given the spatial and resource constraints, crop selection prioritizes species with high yield per square meter, short growth cycles, and compatibility with vertical or tiered systems. The selected crops include leafy greens such as lettuce and spinach, as well as compact fruiting species such as cherry tomatoes and zucchini. Culinary herbs like basil, parsley, and mint are also included for their high density, low resource requirements, and added nutritional and sensory value. Leafy vegetables and microgreens are particularly well-suited for vertical farming applications, which are enabled by the available vertical space. Modular shelving or vertical hydroponic systems could allow two to three tiers of productive area, effectively tripling the yield potential within the same footprint.

Yield estimations under conventional single-layer cultivation suggest a monthly output of approximately 8–12 kg of fresh produce. Under optimized conditions employing vertical farming techniques, yields could realistically reach 15–20kg/month, especially if microgreens are integrated due to their extremely short growth cycles (10–15 days) and high productivity per unit area.

Dietary recommendations for vegetable intake suggest a minimum of 300 grams of fresh vegetables per person per day. For a two-person household, this equates to roughly 18 kilograms per week, or approximately 75 kilograms per month. Comparing this requirement to the potential yields from the greenhouse, it is evident that a standard single-tier system could provide between 10% and 16% of monthly vegetable needs. In contrast, an optimized multi-tier configuration may cover up to 25–26% of the total demand.

The rainwater harvesting system, offering a base availability of 1,500 liters/ month and peak values up to 3,500 liters/month, generally meets the estimated irrigation demands. During winter and spring, water supply is more than sufficient; for instance, an average of 600 liters/month is required in January (at 20 liters/day), representing only 40% of available water. However, during peak summer months, water needs could rise to 4,500 liters/month, exceeding the stored rainwater by up to 2,000 liters. This seasonal imbalance underscores the importance of integrating water-saving technologies and possibly adjusting crop load during high-demand periods.

In conclusion, the bioclimatic greenhouse, despite its seemingly modest 1.75 m2 dedicated cultivation area, possesses significant potential to integrate into the diet of a two-person household. It is projected to cover between 10% and 17% of their annual fresh vegetable requirements, assuming the implementation of optimal and intensive cultivation practices. Beyond the quantifiable output, it is crucial to acknowledge the substantial qualitative benefits of self-production (freshness, reduction in food miles, and individual satisfaction derived from cultivating one's own food).

Conclusions

The research has developed design scenarios that constitute as many validation tests of the potential of the greenhouse-threshold device under different conditions of orientation and functional program. This design experimentation methodology aims to demonstrate the typological versatility of the proposed system and its adaptive capacity to varying conditions at its boundary, confirming the hypothesis of its transversal applicability across configurations of contemporary dwelling.

We structured each design scenario to explore specific architectural variables: alternative spatial configurations, differentiated bioclimatic orientations, diversified functional programs, and variable degrees of permeability between interior and exterior. The comparative methodology adopted allows the verification of how, regardless of contextual conditions, the greenhouse-threshold device maintains its performance effectiveness and qualitative value, invariably constituting an enriching element of the residential experience.

The proposed project for the Panzano District, in Northeastern Italy, demonstrates how innovation and conservation can be successfully combined, creating an intervention model that respects historical memory while looking toward the future, thus promoting a balance between transformation and protection of the site's cultural value. Crucially, the integration of solar greenhouses in the "type 1A" buildings – already subjected to an initial redevelopment attempt according to sustainability criteria by the Monfalcone Municipality – is not merely a technical solution, but a cultural approach that enhances the neighborhood's identity.

The integration of bioclimatic greenhouses demonstrates a measurable enhancement of the building's overall energy and resource performance. Each greenhouse provides an additional 12.1 m² per dwelling unit, predominantly maintaining internal temperatures between 18 °C and 30 °C throughout the year without mechanical conditioning. The greenhouse results in a 20% reduction in thermal and primary energy demand, approximately 70% of which is attributable to the southwest-oriented greenhouse. The application of photovoltaic roofing contributes an additional 12% reduction in non-renewable primary energy consumption.

The rainwater harvesting system ensures irrigation autonomy for up to eight months per year, with a minimum of 30% coverage in summer and over 65% between October and March. Available volumes (1,500–3,500 liters/month) are generally adequate to satisfy irrigation requirements for the 1.75 m² cultivated area, supporting yields ranging from 8–12 kg/month under the conventional configuration. The research confirms that it is possible to achieve significant energy benefits and improve living comfort without betraying the original architectural language.

However, the true strength of this project lies in its replicability. The intervention model defined herein can be adapted and applied in similar contexts, contributing to sustainable and integrated urban regeneration on a broader scale. Looking ahead, we acknowledge that there are still aspects to be explored further, particularly regarding water self-sufficiency within this specific retrofit context. The increasing adoption of advanced computational optimization techniques and smart materials signals a paradigm shift toward more adaptive and performance-driven solutions.

Importantly, our next phase will focus intensively on the compositional, architectural, and technical aspects of the project. Once the performance parameters have been verified and it has been confirmed that this intervention type offers significant improvements over the current situation, we will now concentrate on the form and architectural detail of the solar greenhouse design. This compositional refinement is crucial, as the success of our intervention depends not only on its technical performance but also on its ability to harmoniously integrate with the existing architectural language and enhance the overall aesthetic quality of the built environment.

The further development of the research will also address a key aspect of the proposed intervention's sustainability, namely its economic feasibility. It is indeed necessary to verify that the costs associated with the installation and the maintenance of the bioclimatic greenhouses are balanced by the expected energy and water resource contributions provided by the proposed solution, as determined through an assessment of the avoided costs over the life cycle of the new installation. In conclusion, this project underscores that the integration between historical heritage and contemporary sustainability requirements is not only possible but essential for creating resilient communities that honor their past while embracing their future. The next aspect of our research will ensure that this integration is not just functionally successful, but also architecturally compelling and compositionally coherent.

Acknowledgments

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Bibliography

Afshari, F., E. Mandev, B. Muratçobanoğlu, A. Çelik, and M. A. Ceviz. "Experimental and Numerical Study on Solar Energy Storage in Black-Covered Sunspace Using Water-Filled Tin Cans." *Journal of Enhanced Heat Transfer* 31, no. 3 (2023): 21-44.

Albatici, R., F. Passerini, and J. Pfafferott. "Energy Performance of Verandas in the Building Retrofit Process." *Energies* 9, no. 5 (2016).

Allesina, G., C. Ferrari, A. Muscio, and S. Pedrazzi. "Easy-to-Implement Ventilated Sunspace for Energy Retrofit of Condominium Buildings with Balconies." *Renewable Energy* 141 (2019): 541-548.

Barillari, D., and C. A. Stival. "The Industrial Heritage of the Trieste Shipyard in Monfalcone: Restoring the Garden-City Model in the Residential Typologies of the Panzano District." *Journal of Architectural Conservation* 28, no. 3 (2022): 217-242.

Brunoro, S. "Passive Envelope Measures for Improving Energy Efficiency in the Energy Retrofit of Buildings in Italy." *Buildings* 14, no. 7 (2024).

Catino, C. *Capturing Bioclimatic Greenhouse, Superga*. Turin: 2021. https://accnaturalearchitettura.it/en/capturing-bioclimatic-greenhouse/.

Dodd, T. *Rick Mather Architects: All Glass Extension and House Refurbishment, Hampstead*. 2025. https://www.tdad.uk/home/all-glass-extension-and-house-refurbishment-hampstead.

Donatello, S., M. Cordella, and N. Dodd. *Use-Stage Water Consumption*. 2021.

Elaouzy, Y., and A. El Fadar. "A Multi-Level Evaluation of Bioclimatic Design in Mediterranean Climates." *Sustainable Energy Technologies and Assessments* 52 (2022).

Lacaton, A., and J.-P. Vassal. *Maison Latapie, Floirac*. 2008. https://www.lacatonvassal.com/index.php?idp=25. Accessed 23 Jun 2025.

Lacaton, A., and J.-P. Vassal. "Maison Latapie." In *El Croquis Omnibus: Lacaton & Vassal 1993–2015*, vols. 177-178, 48-57. Madrid: El Croquis, 2017.

Langemeyer, J., C. Madrid-Lopez, A. Mendoza Beltran, and G. Villalba Mendez. "Urban Agriculture—A Necessary Pathway toward Urban Resilience and Global Sustainability?" *Landscape and Urban Planning* 210 (2021).

Limoncin, P., T. Bisiani, and C. A. Stival. "Façade Additive Strategies to Foster a Wider Concept of Comfort." In *Proceedings of the 4th International Conference on Sustainable Development in Civil, Urban and Transportation Engineering*, edited by A. Różański et al., 177-187. Singapore: Springer Nature, 2025.

Lotfinejad, P., A. Tarkashvand, and H. Sanaieian. "A Computational Approach for Integration of Greenhouse and Shanashir to Enhance Thermal Comfort Using the NSGA-II Algorithm." *Building and Environment* 273 (2025).

Ma, Q., X. Chen, X. Wang, W. Gao, X. Wei, and H. Fukuda. "A Review of the Application of Sunspaces in Buildings." *Energy Sources*, Part A 47, no. 1 (2021): 10292-10314.

Ma, Q., C. Xu, X. Chen, W. Gao, and X. Wei. "Experimental and Simulation Research on the Energy-Saving Potential of a Sunspace: An Apartment in Qingdao." *Sustainability* 15, no. 1 (2023).

Mazzeo, D., C. Baglivo, S. Panico, and P. M. Congedo. "Solar Greenhouses: Climates, Glass Selection, and Plant Well-Being." *Solar Energy* 230 (2021): 222-241.

Muhammad, N. S., and M. W. Lin. "Reliability of Rainwater Harvesting Systems Using the Yield-After-Spillage Algorithm." In *Proceedings of the AWAM International Conference on Civil Engineering*, 481-494. 2022.

Niederwöhrmeier + Kief. *Wohnhaus im Knoblauchsland vor Nürnberg*. (Residential building in the Knoblauchsland region near Nuremberg.) 2016. https://www.nkarchitekten.de/ wohnhaus-im-knoblauchsland.

Project Group of Panzano Municipality for the Panzano Recovery Plan. *Panzano Recovery Plan: Building Typologies*. Monfalcone, 2010a.

____. *Panzano Recovery Plan: General Report*. Monfalcone, 2010b.

Rong, X., H. Fang, and C. He. "Renovation Strategies for Green Spaces in Aging Residential Communities in Cold Regions." *Buildings* 15, no. 8 (2025).

Stival, C. A., T. Bisiani, and P. Limoncin. "Criteria for Enhancing Comfort and Liveability through Innovative Façade Interventions." *Architecture, Structures and Construction* 5, no. 1 (2025): 14.

Thebo, A. L., P. Drechsel, and E. F. Lambin. "Global Assessment of Urban and Peri-Urban Agriculture." *Environmental Research Letters* 9, no. 11 (2014).

Turner, V. *The Forest of Symbols: Aspects of Ndembu Ritual*. Ithaca, NY: Cornell University Press, 1970.

Uludaş, M. Ç., E. Tunçbilek, Ç. Yıldız, M. Arıcı, D. Li, and M. Krajčík. "PCM-Enhanced Sunspace for Energy Efficiency and CO_2 Mitigation." *Journal of Building Engineering* 57 (2022).

Valcovich, E., and F. Gadaleta. *Catalogo Panzano 1950–2017*. Monfalcone: Comune di Monfalcone, 2017.

Vukadinović, A., J. Radosavljević, A. Signorđević, and M. Protić. "Influence of Façade Structure, Glazing Type, and Window-to-Wall Ratio on Energy Performance." *Journal of Energy Engineering* 149, no. 1 (2023).

Yao, G., X. Guo, Z. Qian, Y. Pang, Y. Zhang, and C. Xie. "Thermal Buffer Spaces in the Renovation of Rural Dwellings in Cold Regions of China." *Journal of Building Engineering* 99 (2025).

Yeo, U.-H., S.-Y. Lee, S.-J. Park, J.-G. Kim, J.-H. Cho, C. Decano-Valentin, R.-W. Kim, and I.-B. Lee. "Rooftop Greenhouse: Thermal Energy Loads of a Building-Integrated Rooftop Greenhouse." *Agriculture* 12, no. 6 (2022).

Zatta, E., M. Condotta, R. Revellini, and V. Tatano. "Delivering Sustainability in the Italian N-E Built Environment." *Buildings* 13, no. 12 (2023).