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Materials and Components for the Sustainable Retrofitting and Climatic Optimization of Etnean Wineries in Sicily, Italy

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Abstract

The traditional wineries of Mount Etna represent a unique cultural, architectural, and productive heritage, deeply rooted in the region's long winemaking history. However, many of these structures require retrofitting to meet contemporary needs while preserving their historical integrity and environmental significance. An effective approach to the restoration of Etnean wineries should combine innovative and sustainable solutions with traditional techniques, thus fostering a harmonious balance between heritage preservation, energy efficiency, and the reduction of environmental impact. The research focused on the study of several wineries in the Etnean area, identifying recurring typological, technical, constructive, and material invariants that recur across these structures. Based on these findings, compatible interventions on the building envelope were proposed, aiming to improve the indoor hygrothermal performance of wine cellars. These improvements do not only optimize the conditions for wine ageing but also elevate the quality and functionality of indoor spaces. In the current market, marked by a growing demand for high-quality wine, an accurate control of the cellar's climatic conditions is essential for ensuring superior product standards. The proposed interventions incorporate natural materials and components, employing manual or mechanized techniques. Their environmental impacts were evaluated using the Life Cycle Assessment (LCA) methodology to identify the most sustainable retrofit solutions.

Keywords: *vernacular architecture; etnean wineries; sustainable design; life cycle assessment; natural materials*

1. Introduction

Etnean wine, a symbol of Sicilian tradition, originates from the fertile slopes of Mount Etna, where viticulture has been refined over the centuries. The volcanic soil, rich in minerals, and the well-draining substrate (composed by volcanic ash, pumice, and sand) create ideal conditions for vine cultivation, while terracing optimizes the use of Mount Etna's steep slopes. The climate, with significant temperature variations, allows for a slow grape maturation, enhancing its aromas. The Etna wine region is renowned for its DOC wines, produced in accordance with local tradition.

Vineyards are spread along a "C"-shaped belt around the volcano, with different slopes dedicated to specific types of wine production.

Across the globe, traditional wineries consistently highlight the importance of the relationship between the building envelope and the foundation ground. Many studies confirm that thermal stability, provided by contact with the ground, gives traditional underground wineries a competitive advantage over modern aboveground wineries, which rely on HVAC systems for climate control.

As stated elsewhere (Tinti et al. 2015), from the mid-20th century onward, underground wineries were gradually replaced by single-story aboveground structures equipped with air-conditioning systems for controlling temperature and humidity, which led to increase in management costs and energy consumption.

Some researchers attribute up to half of the total energy required for wine production to the use of HVAC systems for regulating indoor temperatures and humidity levels (Tassinari et al. 2011). It is therefore understandable why so much effort has been put in the wine industry, over the past few years, into decreasing energy consumption.

Historic small and medium farm wineries can offer answers to this issue, due to their production capacity, strong local connections, and efficient thermophysical performance (Cañas Guerrero & Martin Ocaña, 2005). A previous study from the authors (Nocera et al., 2020) analysed the energy retrofitting of a traditional Etnean winery, which was built by using bioclimatic strategies in its design.

On-site simulations and measurements assessed the effectiveness of retrofitting interventions such as the installation of aerogel insulation on basalt masonry walls, of hemp insulation on the roof, and the replacement of windows. The results highlighted the importance of insulating roofs and walls while avoiding modifications to the solid ground floor to maintain optimal temperature and humidity conditions for wine fermentation and ageing.

Today, the growing demand for product quality is combined with an ever-increasing demand for construction quality. The design of wineries faces new needs, in ways that require innovative and sustainable solutions, corresponding to the new market conditions and the diversified use of the production territories. Wine production must ensure safety and quality by integrating advanced technologies while preserving the artisanal characteristics that give each product its unique identity.

In response to evolving demands that require Etna's wine production to maintain particularly high production standards, this study aims at the retrofit of a traditional winery on the eastern side of Etna, which presents typological and constructive features that are typical of the area.

In particular, the study proposes a series of sustainable retrofit strategies for building envelope elements, by using sustainable and low impact materials and components that enhance the thermal performance of the building, while ensuring optimal hygrothermal conditions for wine ageing, without relying on HVAC systems.

These interventions are specifically aimed at adapting the thermal transmittance of wall and roof envelope elements in order to comply with the limits set by the Italian Energy Standard. All the proposed stratigraphies are subsequently evaluated using an LCA approach.

The quantification of the environmental impacts of the various materials and components used in the retrofitting strategy, including those due to transportation, on site construction, maintenance and end of life processes, led to determining which of the various options would ensure the best environmental performance.

2. Methodology

The methodology approach involves the following steps (see subsections 2.1-2.3).

2.1. Analysis of typological, technical and constructive invariants of traditional Etnean wineries

The typical wineries of the eastern side of Mount Etna are characterised by building traditions that persist today. The Mediterranean climate has influenced the design of rural houses, which utilize natural materials and bioclimatic strategies to limit winter and summer temperatures variations.

The first phase of the analysis concerned the study of the spatial, functional, typological, technical and constructive invariants that characterize traditional Etnean wineries. The most typical features of these wineries (planimetric systems, construction technologies and base materials used) were collected. This analysis was carried out by referring to previous studies (Palumbo, 1991) and to surveys carried out both on site and using Google Earth.

The initial outcome of this investigation phase was the production of a series of fact sheets (Fig. 1) on several traditional Etna wineries. The sheets contain the following information:

- Name of the winery or building
- Location
- Plan and a representative section
- Typological description of the cellar
- Construction techniques and materials used
- Additional notes

Furthermore, the second outcomes of this investigation was the identification of a traditional winery that could act as a zero case to be retrofitted. The elements that characterized the typical winery will be presented in section 3.

2.2 Retrofit hypotheses and thermal envelope design

Based on the technical and constructive information collected in the previous phase, typical stratigraphies were developed for the solid ground floor, as well as for the vertical and roof envelope elements. As previously mentioned the first step toward enhancing the performance of these elements and therefore to improve the expected hygrothermal performance of traditional Etnean wineries, is ensuring compliance with Italian energy regulations.

The Italian standard (D.M. 26 June 2015) determines minimum energy efficiency requirements for building envelope elements, depending on the climate zone. The proposed case, a winery in *Piedimonte Etneo*, is located within climate zone C, which requires the following minimal thermal transmittance values:

- 0.34 W/m^2K for exterior walls,
- 0.33 W/m^2K for the roof system,
- 0.38 W/m^2K for the solid ground floor.

This study proposes several technological retrofits for the envelope elements of wineries to improve the indoor thermal stability and ensure optimal hygrothermal conditions for wine fermentation and ageing, while complying with Italian regulations. In continuity with a previous study by the authors (Nocera et al. 2020), the chosen retrofitting interventions refer only to the vertical and roof elements, leaving the solid ground floor element uninsulated.

For the sake of brevity, only the proposal for the retrofitting of vertical envelope elements is presented below. All the following retrofit scenarios use a first layer of lime and gypsum smoothing coat.

This layer serves to even out the indoor surface of the basalt stone masonry and favours the subsequent application of an insulation layer.

- STR.01: calcium silicate panels, lime plaster
- STR.02: light earth blocks manufactured on site (with wooden support structure), raw earth plaster
- STR.03: Hemp fibre panel insulation (with wooden support structure), extruded raw earth finishing panels, raw earth coating
- STR.04: Cast-in-place hemp lime mix (with wooden support structure), hemp lime thermal plaster
- STR.05: Cork insulating panel, lime plaster

2.3 LCA analysis of the retrofit strategies

Lastly, the sustainability of retrofitting interventions are confirmed by a life cycle analysis (LCA). This analysis examines the impacts of key material and energy inputs across all life cycle stages: from the extraction and sourcing of raw materials (upstream), through transport, production, construction, installation, and maintenance, to their final disposal or recycling. The LCA was developed in accordance with ISO 14040 and ISO 14044.

The system boundaries include all the materials and processes necessary for the retrofitting of the walls, from cradle to grave. The analysis is referred to a functional unit of 1m^2 of wall with thermal performance of U=0.30 W/m^{2}K.

The implementation of this method has enabled the quantification of emissions into the air, water and soil.

The Emission Factors (EFs) for the Carbon Footprint (Global Warming Potential) were assessed using the CML-IA method in SimaPro 9.0.0, based on data from the Ecoinvent 3.6 database. The AWARE method was used to assess the Water Footprint, while the Cumulative Energy Demand (CED) method was used to evaluate the Embodied Energy values.

The analysis is based on several key assumptions. A life cycle of 100 years was assumed for the walls. Emissions associated with the transportation of materials and components were estimated by considering the origin and treatment of the materials in relation to the location of the winery. A distance of 100 km was assumed for sand, fibres, insulation and cladding materials, while earth is assumed to be extracted within a 50 km radius. For assembly and installation, the consumption of materials and energy (electricity and diesel) for processing each component was based on the operations carried out using machinery and equipment. In the case of maintenance, it is assumed that the finishing materials will be replaced every 20 years. Both recycling and landfill disposal are considered as options for end-of-life stage, depending on the nature of the materials, while the emissions related to the transportation (by truck) of materials to a hypothetical waste management facility, located at a distance of 50 km, were also included.

3. Typological, technical and constructive characteristics of Etnean wineries

The wineries of eastern Etna have specific typological and constructive features that have been conditioned by the Mediterranean climate and the availability of local materials. A detailed analysis of Etna's wine cellars has revealed a series of typological, constructive and material invariants that provide a foundation for determining the appropriate intervention strategies.

From a typological point of view, the rural dwellings (locally called *masserie*) of the Etna region can be divided into the following categories (Palumbo, 1991):

- *Single-storey buildings:* consists of simple volumes with transverse walls dividing the spaces and a pitched roof resting on the perimeter walls; in more complex layouts, volumes are arranged around a central courtyard.

- *Buildings on slope:* structures built on natural elevations, with the main residence on the upper level and the production rooms below. This configuration optimized the flow of must from the pressing area to the cellar and ensured protection.
- *Closed-courtyard buildings:* multi-level structures arranged around a central courtyard designed to provide protection, privacy, animal shelter, and a communal gathering space for agricultural communities.
- *19th-century evolution:* buildings open to the exterior, featuring large windows, balconies, and terraces supported by arcades.

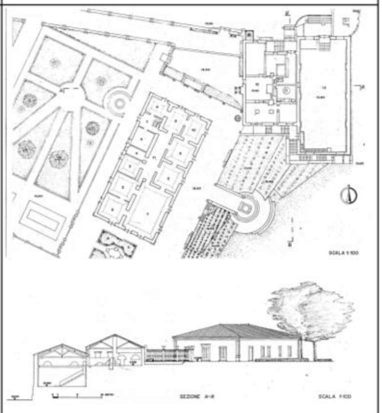
Denominazione	CASA GRASSI A REGIA CORTE
Localizzazione	Piedimonte, Via Sante Puglisi, 8, (CT)
Planimetria	
Descrizione tipologica	Al fabbricato originale si affiancano degli ampliamenti al corpo di fabbrica dedicati alla produzione e conservazione del vino. Il volume situato a Nord-Est del complesso residenziale. Le stanze hanno diversa altezza per facilitare il trasporto del mosto nei vari barili. Dal palmento si accede alla cantina con una scala.
Tecniche costruttive	Le parerti verticali sono costituiti da blocchi di pietra lavica di 60 cm di spessore che rappresentano la parte strutturale dell'edificio. I volumi del palmento e della cantina si trovano a quote altimetriche diverse. Coperturacostituita da capriate e listelli.
Note	Attualmente il fabbricato fa parte di una societá agricola.

Fig. 1 – *Example of a factsheet for Casa Grassi winery at Piedimonte Etneo, in the Etnean area* (Sheet by Tushi Artiol, 2025; source Palumbo, 1991).

Traditional masonry building techniques have evolved over time. Initially, irregular blocks of stone were bound together with mortar. Later, stones were roughly shaped and laid with layers of broken bricks to create a more regular structure. Between the 17th and 18th centuries, formwork was introduced, and stone placement improved, resulting in 65-75 cm thick load-bearing walls. Partition walls on the lower floors were similar in thickness to the load-bearing walls in order to resist the thrust of the vaults and ensure the stability of the upper floors; wall thicknesses were reduced on higher floors. On the upper floors, partitions were often constructed using timber framing and reed panels, which provided both lightness and durability. Foundation walls were thicker than aboveground ones, with an average depth of approximately one meter.

Wineries that were built on rocky ground had shallower foundations, more stability and were better protected from moisture; they also had the advantage of occupying areas that could not be cultivated, while the rocky ground provided a naturally paved base for courtyards. Separation from the ground was provided by a crawl space, while the underground rooms contributed to internal hygrothermal regulation.

The floor above the ground level was often built with stone vaults, while the upper floors were constructed with a double-timber-framed floor with beams, joists and planks. Some buildings feature false vaults made of reed structures covered with gypsum plaster.

Timber roofs consisted of rafters aligned parallel to the slope and resting either directly on the edges of the walls or on timber trusses. This main framework bore the weight of beams, that in turn supported vertical wooden slats or planks, on which terracotta tiles were placed.

Openings were kept small to minimize summer overheating.

Materials reflected the availability of local resources. Lava stone, although difficult to work, was widely used for masonry and simple architectural elements, since it was valued for its density and its effectiveness in enhancing indoor comfort by regulating heat flow.

Limestone from Syracuse, was used for decoration, such as on door frames and other ornamental details.

The choice of flooring materials varied according to the intended function: courtyards were often left with their natural surface, while wine press areas (*palmento*) were paved with lava stone or a mixture of lime, volcanic sand and crushed terracotta (known as *battume*). Interior floors were paved with terracotta tiles, plain and simple in workers' areas, yet elaborately decorated with geometric patterns in the owners' quarters. More modest dwellings used lava stone slabs, which were strong enough to withstand the weight of barrels.

4. Retrofit strategies and thermal properties assessment

Based on the collected information, a prototype winery has been designed, reflecting the representative typological, technical and constructive features of wineries on the eastern slopes of Mount Etna.

The representative winery is located in *Piedimonte Etneo*; it consists of a single-story structure with a height of 6 meters. The load-bearing walls, made of 70 cm-thick squared basalt stone, are coated with lime plaster. The roof features two slopes supported by wooden trusses and covered with terracotta tiles. The floor consists of large stones and soil, a layer of smaller stones with mortar, and a basalt stone slab finish.

For each hypothesized intervention, an assessment of the expected thermal performances was carried out according to the ISO 13786, to comply with D.M. 26 June 2015. Thermal properties of materials were derived from authors' previous works (Dipasquale et al., 2025, Giuffrida et al., 2021). All stratigraphies are homogeneous in terms of thermal performance, as their thermal transmittance equals 0.30 W/m^{2}K. Thicknesses of materials and components used are shown in table 1. Note that the use of natural materials has led to an increase in the insulation thickness, due to their lower thermal performance. This aspect involved a careful study of the implementation phases of the interventions. For each hypothesis, the equipment and machinery used were listed as well as the operational phases for its implementation. This analysis represents a first step towards the life cycle assessment phase.

Table 1 – *Composition of walls after retrofit* (Giuffrida, 2025).

	Layer	t_{tot} [m]	t [m]
STR.01	Lime plaster	0.87	0.03
	Basalt stone masonry		0.70
	Calcium silicate board		0.15
	Lime-gypsum plaster		0.02
STR.02	Lime plaster	1.01	0.03
	Basalt stone masonry		0.70
	Light earth		0.25
	Raw earth render		0.030
STR.03	Lime plaster	0.85	0.03
	Basalt stone masonry		0.70
	Hemp fibre panel		0.10
	Extruded earth panel		0.022
	Raw earth coating		0.002
STR.04	Lime plaster	0.92	0.03
	Basalt stone masonry		0.70
	Lime hemp insulation		0.15
	Lime hemp thermal plaster		0.04
STR.05	Lime plaster	0.87	0.03
	Basalt stone masonry		0.70
	Cork insulation		0.12
	Lime-gypsum plaster		0.02

5. LCA of the retrofit strategies

The table below (see table 2) shows the environmental impacts - Carbon Footprint (CF), Water Footprint (WF), and Embodied Energy (EE) - of the different stratigraphies after retrofit.

Table 2 – *LCA results* (Giuffrida, 2025).

Wall solution	**CF** [$kgCO_2eq$]	**WF** [m^3]	**EE** [GJ]
STR.01	116.39	3.72	1.32
STR.02	16.80	10.81	0.32
STR.03	31.33	5.26	2.28
STR.04	36.18	5.07	0.99
STR.05	30.71	13.25	2.34

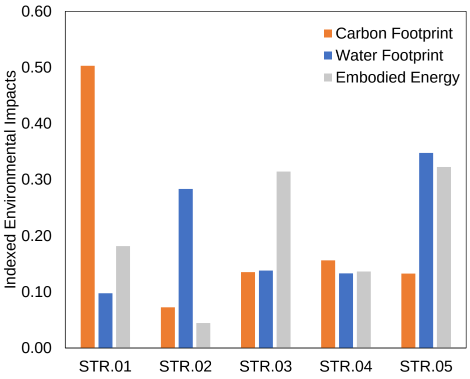


Fig. 2 – *Indexed environmental impacts* (Giuffrida, 2025).

Figure 2 shows the indexed environmental impacts. It is noted that the STR.02, using a light earth mixture as insulating material, has the lowest CF. This is followed by STR.05 and STR.03, respectively, which, despite the use of prefabricated components, employ fewer and more thermally efficient materials. The STR.01 has the greatest CF due to the use of calcium silicate boards.

The Water Footprint (WF) analysis shows that the STR.05 stratigraphy has the greatest WF, followed by the STR.02 (whose WF is mainly due to the use of straw fibres for the light earth mix). Please note that in the case of STR.02, this impact could be lowered by using fibres that are by-products of agricultural supply chains. The STR.01 has the lowest WF.

The Embodied Energy analysis (including both renewable and non-renewable primary energy resources) shows that the STR.05 has the highest embodied energy, followed by STR.03, due to the use of prefabricated insulation panels. The lowest EE belongs to STR.02, which is manufactured on-site as STR.04.

5. Conclusion

Historic buildings for agricultural production represent a valuable architectural heritage that must be preserved and restored in harmony with modern environmental concerns. For traditional wineries on Mount Etna (Sicily, Italy), this involves redesigning the building envelope to enhance the indoor hygrothermal performance, ensuring optimal conditions for wine production and a low environmental impact.

This work presents several intervention strategies on the vertical envelope of a representative traditional Etnean winery. Specifically, five interventions are selected, each using materials of different origins (natural or industrial) and varying manufacturing processes (prefabricated or cast on-site). This approach aims to identify the alternative with the lowest environmental impacts.

The methodology adopted in this study is structured into three main phases. The first phase involved analysing the typological, technical, constructive, and material characteristics that define traditional Etnean wineries. The second phase focused on developing thermal retrofit hypotheses and designing improvements for vertical envelope elements. Lastly, the third phase consisted in assessing the environmental impact of the retrofit strategies through a Life Cycle Assessment (LCA), by evaluating Carbon Footprint (CF), Water Footprint (WF), and Embodied Energy (EE).

The results show that wall stratigraphies using mineral-based prefabricated panels (STR.01) have higher CF compared to bio-based materials as light earth insulation (STR.02), manufactured on site. Moreover, the STR.02 has also the lowest EE. Nonetheless, the light earth stratigraphy has one of the highest WF value, while calcium silicate insulation (STR.01) has the lowest.

The obtained results highlight the critical role of natural materials in shaping sustainable retrofit strategies. Additionally, they confirm the significance of Life Cycle Assessment as a fundamental tool for promoting more sustainable and regenerative construction approaches.

Future research will focus on validating the efficiency of these interventions through hygrothermal simulations and integrating economic analysis to assess cost-effectiveness. Further exploration of this topic could concern the implementation of real-time monitoring systems and the development of digital twins for continuous performance evaluation and optimization of traditional wine cellars behaviour.

Recovery and sustainability are, today more than ever, two key concepts in the design and revitalization of traditional wineries. The challenge lies in finding the right balance between meeting high performance standards and preserving the historical memory embodied by these architectures.

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