

Article

Cost-Effectiveness Evaluation of Nearly Zero-Energy Buildings for the Aging of Red Wine

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Abstract: Achieving the best energy performance has become an important goal. The European Union has consequently developed legislative measures that introduce the concepts of nearly zero-energy buildings and cost-effectiveness during life-cycle. We use these concepts, looking for the design of energy-efficient wineries, while reducing wine production costs. The research method is based on the monitoring of temperature and humidity of 12 red wine aging rooms of representative construction designs with almost zero energy consumption that together with the economic data obtained from construction cost update, determine a parameter that has been called “construction effectiveness”. This parameter allows the evaluation of the cost–benefit ratio of each of the analyzed constructions. The results obtained demonstrate that adequate conditions can be achieved for the wine aging with zero-energy buildings, although there are notable differences in cost, damping effectiveness, and resulting hygrothermal environment depending on the type of building. The correlation between performance and construction costs shows large differences in cost per unit of damping achieved: 0.5–2.7 €/m² for temperature and 0.6–5 €/m² for relative humidity. With a correct design, the differences between typologies can be reduced or even non-existent. The results obtained can be a valuable tool to promote the design of zero-energy warehouses.

Keywords: wine; winery; aging; zero-energy building; cost; effectiveness



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1. Introduction

Achieving the best energy performance of member countries and the reduction of greenhouse gas (GHG) emissions has become an important goal for the European Union (EU). To achieve the energy and climate objectives set by the EU itself for 2030, the European Commission has been developing various legislative measures that culminated in 2016, with the adoption of a package entitled “Clean energy for all Europeans”. Among the legislative proposals included in this package is a revision of the 2010 Directive on the Energy Performance of Buildings (EPBD), which already contained several provisions to improve the energy efficiency of new or existing buildings. Thus, the Buildings Directive that was initially drafted to improve energy efficiency under the 2020 climate and energy package will continue to be applied in this next decade to help meet the climate and energy objectives for 2030. The recast of EPBD introduced the concept of nearly zero-energy buildings and requires that buildings must be cost-effective during their life-cycle.

The wine industry is one of the sectors most affected by climate change [1] but it is also a sector that contributes significantly to global warming [2] by producing approximately 0.3% of annual global greenhouse gas emissions [3]. At the winery stage 81% of the emissions occurred, and one of the main contributor is the electricity used in the winery (10%) [2]. The energy-intensive use of energy is, mainly, for cooling [4–7] and ventilation,

since high temperature provoked negative effects on wine quality [8]. The EU remains the largest wine market and about 1750 million kWh/year is estimated to be consumed in wine production in the EU, which is mainly supplied by electricity [9].

Taking into consideration that ‘cost optimality’ and ‘nearly zero-energy buildings’ are two fundamental concepts within the current EU policy related to the energy performance of buildings and climate change mitigation [10] the winegrowing industry required the adaptation of the wineries in search for energy efficiency while reducing wine production costs. Therefore the design of energy-efficient cellars is increasingly gaining importance [11–15].

To reduce the environmental impact of wine production, as well as to lower costs, different studies on wineries have been performed in recent years. Research had been developed to reduce consumption during the cold stabilization by optimization of equipment [5], in air conditioning [9] or even evaporative cooling [6]. In terms of the building itself, Benni et al. [16] or Mazarrón et al. [17] compared design effectivity considering above-ground warehouses and underground constructions. Additionally, renewable energies have been proposed to reduce energy dependence [8,18].

Since the implementation of energy implies a huge investment, different research has focused on energy efficiency [19]. Regarding this, as well as the increase of temperatures due to climate change, passive performance of wineries must be considered to be the main strategy with increasing importance [11–15]. Further to competitiveness and promotion of zero-energy buildings in all the sectors [14,15,19,20]. Against this backdrop, underground wineries had become interesting because of their high thermal mass which avoid fluctuations of temperature in above ground constructions, such as had been demonstrated in previous research [11,21], even in traditional wine cellars in Spain [22]. Given this performance, underground constructions [23], and basement [24] had been analyzed as zero-energy buildings. This research mainly focused on specific aspects that influence indoor atmosphere, such as architectural elements [25], type of retrofit interventions [26], ventilation [27,28], infiltration [29] or even the surrounding ground temperature [21]. However, one of the main barriers implementing energy efficiency strategies in the industrial sector are economic and financial barriers [14], despite the economic benefits in terms of productivity because of energy efficiency in the industry [30]. Sanz [11] analyzed the cost-effectiveness of passive strategies for the envelope of a winery located in Argentina. Accorsi et al. [31] studied warehouse building design to minimize the cycle time (average duration of the pickup and drop-off activities), the total cost, and the carbon footprint of the storage system over its lifetime. However, there had not been found an analysis in which the energy efficiency in the wineries was compared to the construction budget.

Our study moves from these considerations with the aim to analyze the correlation between the effectiveness and the cost of constructive solutions adopted in underground, basement, and buried warehouses. The results obtained can be a valuable tool to promote the design of zero-energy warehouses. The research is part of the project “Bioclimatic design strategies in cellars as a model of almost zero energy consumption buildings”, financed by the Spanish Ministry of Economy and Competitiveness. Within this project, the research and article focus on a total of 12 different types of zero-energy buildings that do not require air conditioning systems, and which are currently used for aging quality wine.

2. Materials and Methods

The wine sector has grown exponentially in recent years as a result of the high demand for this product in the market. Spain is one of the three largest world wine producers and a world leader in the production of grape must and wine alcohols [32]. According to the National Institute of Statistics in recent years, the total number of warehouses in Spain has grown to 4373 in 2018. Given this magnitude, the research was limited to two aspects: (i) the search for wineries with quality wine production; (ii) that said wineries did not use energy for the maintenance and conservation of wine, taking advantage of the natural conditions of the building itself and, therefore, being able to classify them as a “zero-energy

building". In this section, the wineries selected for the research are described as well as the research methods and procedure followed to carry out the study.

2.1. Warehouses Analyzed

As part of the project "Bioclimatic design strategies in cellars as a model of almost zero energy consumption buildings", 12 wineries have been selected located in Spain in two reference producing regions, Rioja and Ribera del Duero (Figure 1). These wineries are representative of different construction solutions that do not use air conditioning systems and that make quality wines. Specifically, these are 6 basement constructions, 4 underground and 2 buried (Figure 2) that belong to the Castillejo, Cillar de Silos, Gormaz, Ibañez Blanco, Martínez Lacuesta, Puelles, Valduero, Valsotillo, Viña Olabarri, and Viña Vilano wineries. No surface wineries were selected due to their limited thermal inertia which makes them dependent on air conditioning for the aging of quality wines and, therefore, they are not classifiable as "zero-energy buildings".

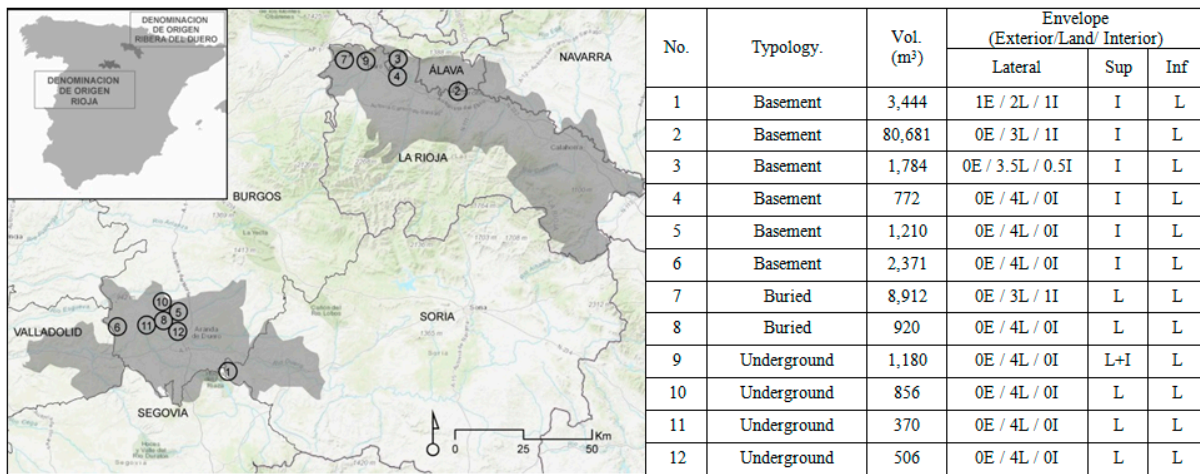


Figure 1. List and location of monitored aging rooms.

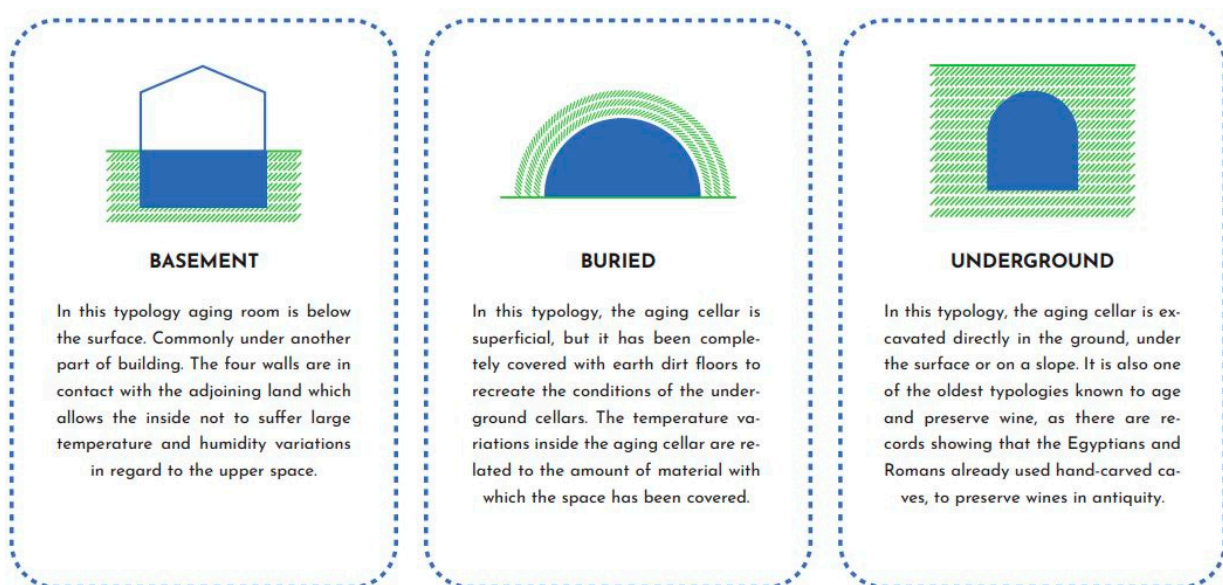


Figure 2. Type of analyzed warehouses.

The underground typology is one of the oldest typologies known to age and preserve wine, as there are records showing that the Egyptians and Romans already used hand-

carved caves, to preserve wines in antiquity. As shown in Figure 2 the aging room is excavated directly in the ground, under the surface, or on a slope. In the basement typology aging room is below the surface, commonly under another part of building. In this case, the four walls are in contact with the adjoining land which allows the inside not to suffer large temperature and humidity variations regarding the upper space which, nevertheless, does not present as much thermal inertia, this one being separated by a floor plant framing. Finally, in the buried typology, the aging room has been completely covered with earth to recreate the conditions of the underground cellars. The temperature variations inside the aging cellar are related to the amount of material with which the space has been covered.

2.2. Methodology

The methodology used in the research begins with the selection of case studies that meet the requirements established in the previous section, to subsequently carry out field work for the survey and the volumetric and constructive characterization of each of the selected warehouses.

The quantification of the updated cost of each building has been carried out based on information provided by the wineries (projects, work certifications, etc.) as well as the documentation collected during the site visits. The construction details, together with the original plans, allowed the obtaining of the budget items and the necessary measurements to obtain an updated budget of the aging unit construction costs.

The site visits, in addition to allowing real surveys and verification of the information provided by each of the participating warehouses, served to carry out on-site tests to verify the type of land. To this end, a campaign of non-destructive surface hardness measurements was carried out with Shore durometers or mechanical resistance using the Schmidt sclerometer, dynamic elasticity modulus by ultrasound and moisture content in the ground using a hygrometer.

Figure 3 summarizes the methodology followed in the research.

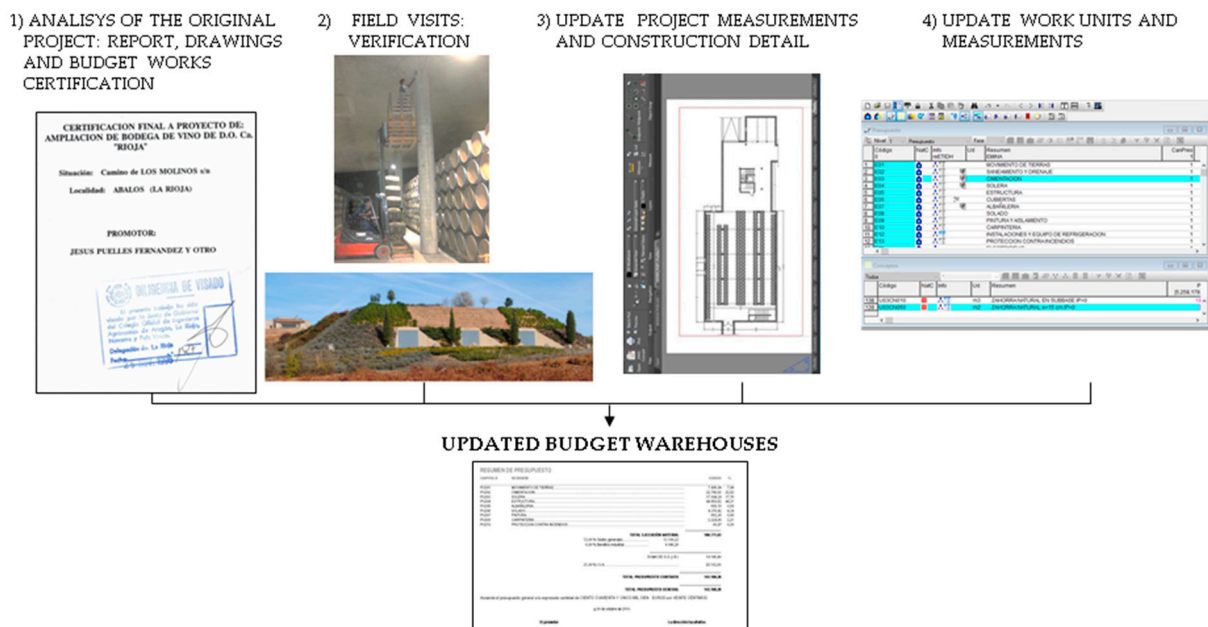


Figure 3. Example of the process of updating the budget of a warehouse.

2.3. Methods

As for the methods used in the investigation, it is based on the monitoring data of the selected warehouses that together with the economic data obtained from the construction cost update, allows us to determine a parameter that has been called “construction

effectiveness". This parameter facilitates an evaluation of cost–benefit ratio of each of the analyzed constructions.

2.3.1. Monitoring of the Indoor Hygrothermal Environment

The monitoring was carried out using Hobo[®] brand temperature and humidity recorders and sensors. The accuracy of the sensors is greater than ± 0.3 °C and $\pm 3\%$ R.H., with a resolution of 0.03 °C and 0.03% R.H. The monitoring period was 1 year, using a measurement interval of 15 min. The data collection has been carried out in accordance with the recommendations contained in EN 17267:2020 and EN 62974-1 [33,34]. With this, a complete record of the behavior of buildings in both summer and winter has been obtained.

The monitoring conditions remained homogeneous throughout the investigation, adapting to each type of winery. Most of the aging rooms are very uniform on the horizontal plane but have a marked vertical stratification, especially in the summer months [35]. For that reason, temperature differences in the vertical plane were monitored, at least at a central point in the aging room. The sensors were installed at different equidistant heights to record the entire volume occupied by the barrels. Regarding underground wineries, although they generally have a very stable temperature, their length and the differences along the horizontal plane required the placement of several sensors along the tunnels.

2.3.2. Construction Effectiveness

The thermal effectiveness of the construction has been quantified through the ability to dampen outside temperature variations, equivalent to other previous work in warehouses [12,17]. Specifically, thermal damping has been calculated as a percentage of the variation of the external temperature:

$$\text{Damping (\%)} = \frac{\Delta T_{\text{outdoor}} - \Delta T_{\text{inside}}}{\Delta T_{\text{outdoor}}}, \quad (1)$$

Quantification of the effectiveness of the construction has been carried out in three levels: annual damping, average monthly damping, and average daily damping. The average value of the set of sensors located in the building has been calculated, as a representative value of the wine contained in the set of barrels, which will be homogenized before bottling.

Annual damping has been calculated from the maximum and minimum values recorded in a year; the average monthly damping is the average of the 12 monthly damping values, calculated from the maximum and minimum values recorded in each month; the average daily damping is the average of the 365 daily damping values, calculated from the maximum and minimum values recorded on each day.

2.3.3. Cost Determination

One of the key aspects of the investigation was to determine the constructive cost of each type of winery. The budget for their execution has been structured in three main chapters: excavation, civil works, and installations, to homogenize the items and allow comparison between them. The information used in this section is based both on the documentation provided by the wineries or collected in the literature, and on the field study carried out to identify and verify the materials, techniques, and construction systems used in each of the buildings.

The excavation chapter includes all the works related to earthmoving, substantially differentiating the items included depending on the specific type of winery to be considered. This chapter not only contemplates the excavation process itself, characteristic of the underground or basement warehouse, but also the excavation to allow the access of the machinery through forklifts for the underground cellars. In both cases, the type of terrain is taken into consideration, the type of machinery most appropriate to each case—light or heavy—the transfer of the machinery to the place of execution of works, especially in the case of underground warehouses due to their specificity, as well as the accessibility

of said machinery to the excavation site. This chapter also includes the transfer of land from excavation to landfill or its deposit at the place of extraction, the cost of execution of ventilation chimneys in underground warehouses as well as the indirect costs that, in the latter, take on particular relevance due to the need to have generators, to give power to the drilling machines, and the necessary permits of the administration for the realization of blasts with the hiring of specialized personnel for their control and execution. Finally, this chapter includes the execution of ventilation chimneys for underground cellars, which, in the case of buried and basement chimneys, are part of the civil works.

The civil works chapter includes both the execution of the structure: foundation, containment, and vertical and horizontal structure in the case of buried warehouses and in the basement, as well as the incorporation of structural reinforcements: continuous (with the execution of vaults) or punctual (preparation of periodic reinforcement arches) in the case of underground warehouses. In both cases, reference costs were used for the execution of the construction systems considering the materials and techniques used. In this regard, it is worth highlighting the differences found in the underground warehouses, in such a way that while in the traditional ones the material used in the reinforcement is made of stone or solid brick, in the newly executed warehouses, greater systems are used, performance such as THN-type metal frames or mounting trusses and their combination with Bernold plates (metallic plates that are used as a support for filling gaps and areas that have suffered a landslide) for shoring and subsequent spraying of concrete, allowing a greater volume of execution with great safety.

Finally, the installation chapter includes the mechanical installations available in the different warehouses, these being lifting elements such as forklifts for the transport of material and electrical installations for lighting the warehouses.

3. Results and Discussions

3.1. Monitoring of the Indoor Hygrothermal Environment

Most buildings have great internal thermal stability (Table 1), with average annual values of daily variation lower than 0.2 °C/day (Figure 4). Only warehouse 11 has higher values, reaching 1 °C during the summer months (May–July). This warehouse is also one with the largest annual amplitude of those analyzed (Table 1).

Table 1. Representative values of the internal temperature in each of the monitored aging rooms.

Typology	Average	Mean	Dev. Est.	Variance	Kurtosis	Coef. Asymmetry	Annual Breadth	Min	Max
1	13.0	12.4	3.2	10.3	−1.3	0.3	11.2	8.3	19.5
2	16.1	16.0	1.7	2.9	−1.4	0.1	5.9	13.2	19.1
3	14.8	14.6	3.5	12.4	−1.4	0.1	11.5	9.4	20.9
4	14.4	14.2	3.2	10.2	−1.4	0.1	11.2	8.9	20.1
5	13.2	12.5	3.1	9.7	−1.5	0.2	9.6	8.7	18.3
6	13.0	12.3	3.0	9.3	−1.1	0.5	10.7	9.0	19.6
7	14.4	14.1	2.4	5.8	−1.4	0.1	9.4	10.1	19.4
8	12.6	12.5	1.7	2.8	−1.4	0.1	7.4	8.3	15.7
9	11.6	11.4	2.1	4.4	−1.2	0.0	8.9	6.9	15.8
10	10.3	10.3	0.8	0.6	−0.9	0.1	3.9	8.5	12.4
11	9.1	9.3	1.6	2.4	−1.0	−0.3	11.8	3.5	15.3
12	9.6	9.4	1.7	2.9	−1.3	0.2	9.1	6.3	15.4

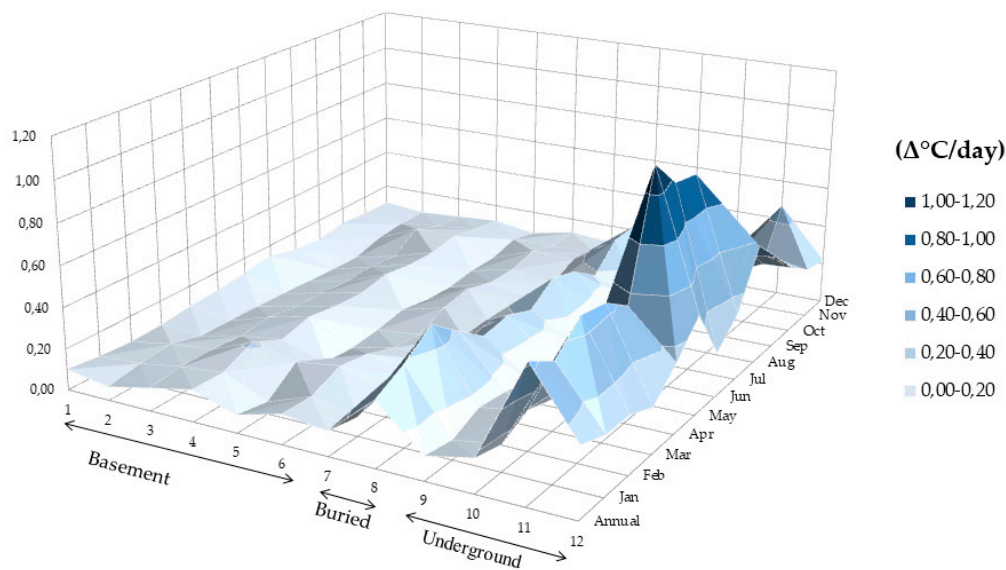


Figure 4. Mean daily temperature stability ($\Delta^{\circ}\text{C}/\text{day}$) inside the buildings analyzed.

This circumstance can be explained by the high rate of natural ventilation that this winery presents [36].

Despite this, the average annual indoor temperature ranges between 9.1°C and 16.1°C , with highs between 12.4°C and 20.9°C and lows between 3.5°C and 13.2°C . In this sense, attention should be drawn to the differential values between the warehouses analyzed in such a way that, while the basements show an average annual temperature of 14.1°C with annual thermal amplitudes of 10.0°C and maximum that reach 19.6°C on average; in the case of buried, these values are reduced to 13.5°C , 8.4°C and 17.6°C respectively; and, in the case of underground, these values are 10.2°C , with thermal amplitudes similar to those buried with 8.4°C and maximum of 14.7°C . These values show the greater thermal stability of traditional underground warehouses compared to the most modern warehouses, basement and buried, producing discrepancies only when the ventilation rates are high, as indicated above.

In this regard, it should be noted that the bibliography points out the importance of maintaining a constant low temperature in the winery, to produce a quality wine and reduce losses [37]. Although an optimal range has not been established, several authors point out that if the temperature rises above $18\text{--}20^{\circ}\text{C}$, the quality of the wine decreases [38–40] and evaporative losses occur [41,42]. It is also accepted that temperatures below $4\text{--}5^{\circ}\text{C}$ slow the aging of the wine [24]. Therefore, a range of acceptable comfort temperatures can be set between $5\text{--}18^{\circ}\text{C}$ [12].

According to the literature, additionally to the constant low temperature, it is important to preserve a high relative humidity, greater than 60%, in the winery to diminish evaporative losses, provided that ventilation is adequate to prevent the appearance of harmful mold [37]. The variation of the indoor relative humidity recorded in the different wineries also shows discrepancies depending on the construction typology of the warehouse. It is observed that compared to the average humidity of 77% of the basement warehouse, the relative humidity percentage rises to 80% in the buried ones and 94% in the case of the underground ones. It should be noted the variability found in the relative humidity of the warehouses, with values ranging on average between 73% and 97%. The greatest differences in the annual minimum of each winery ranging between 37% and 73%. However, those differences were damped for each typology with average of 47%, 50%, and 59% in the basement, buried, and underground, respectively. This implies that the difference between the buried warehouses and the underground ones reach 17% in the annual averages, reducing to 14% those of the basements when compared to the underground ones. Despite this, the daily variations are not significant, ranging between 1% r.h. and

5% r.h. but with maximums that reach 9% r.h. in some types of warehouses and specific months.

Therefore, contrary to the statements included in the aspect of internal temperature, the relative humidity inside presents greater variability, a statement that had already been collected by other authors previously [43].

3.2. Effectiveness of Constructive Solutions

All the analyzed warehouses have a great effectiveness in dampening the temperature and relative humidity variations of the outdoor environment (Figure 5). Although the maximum temperature is dampened by the high thermal inertia of the cellars, the same does not happen with the maximum relative humidity, which becomes similar indoors and outdoors. This circumstance shows that similar to those reported in the literature [44,45], compared to the temperature the warehouse has great stability with very damped temperatures equivalent to the annual average. However, the relative humidity (Figure 5) is conditioned, mainly, by the type of ventilation of the warehouse [36].

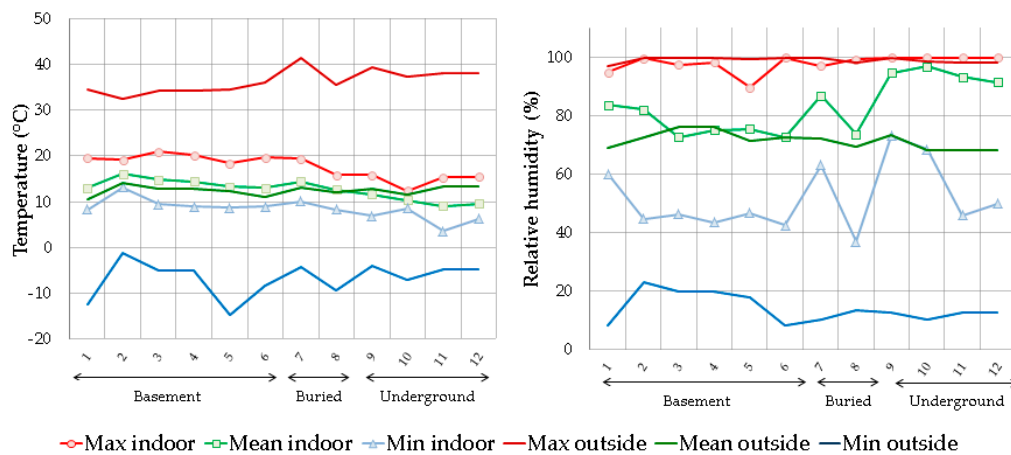


Figure 5. Annual temperature and relative humidity differences between the inside and outside of the warehouses.

Analyzing in detail each of the parameters, with respect to temperature, the annual thermal damping exceeds 70% in all the buildings analyzed (Figure 6a) and mostly greater than 90% in the case of monthly thermal damping (Figure 6b) due to the thermal inertia of the building. The effectiveness of the construction tends to grow as the thermal inertia of the building increases, being therefore more effective in the case of underground wineries with respect to basements and buried, except in specific cases, as can be seen in warehouse 11 and indicated above.

The great thermal inertia of the analyzed warehouses allows the maintenance of a stable interior environment, with a negligible effect of the daily oscillations of the exterior environment. Thus, the damping is higher than 93% if the daily damping throughout the year is considered, with the average of the set of buildings being 98% (Figures 6 and 7). However, if we consider the monthly scale, the damping is higher than 88%, with an average of 93% (Figures 6 and 7).

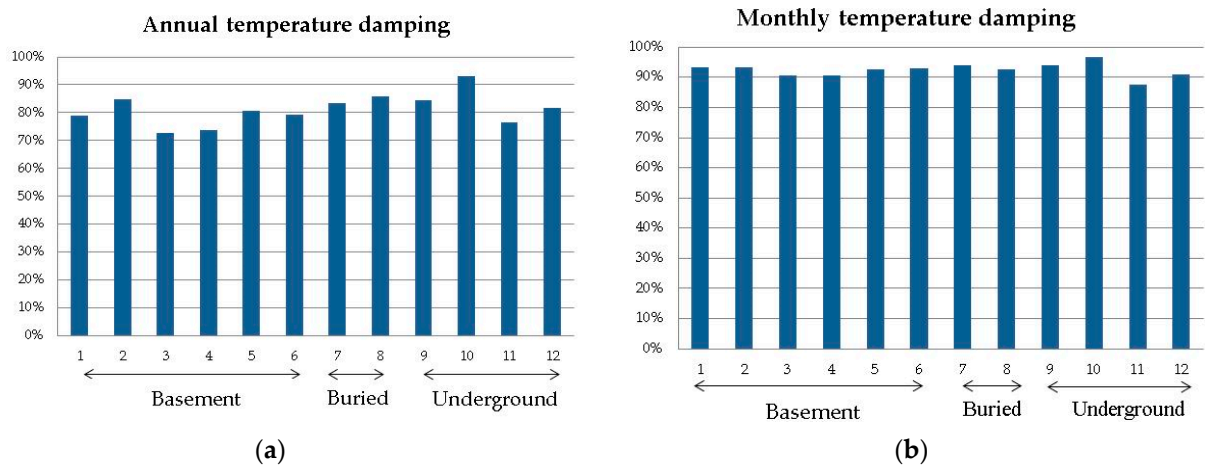


Figure 6. Damping of temperature in buildings analyzed (a) Annual temperature damping; (b) Monthly temperature damping.

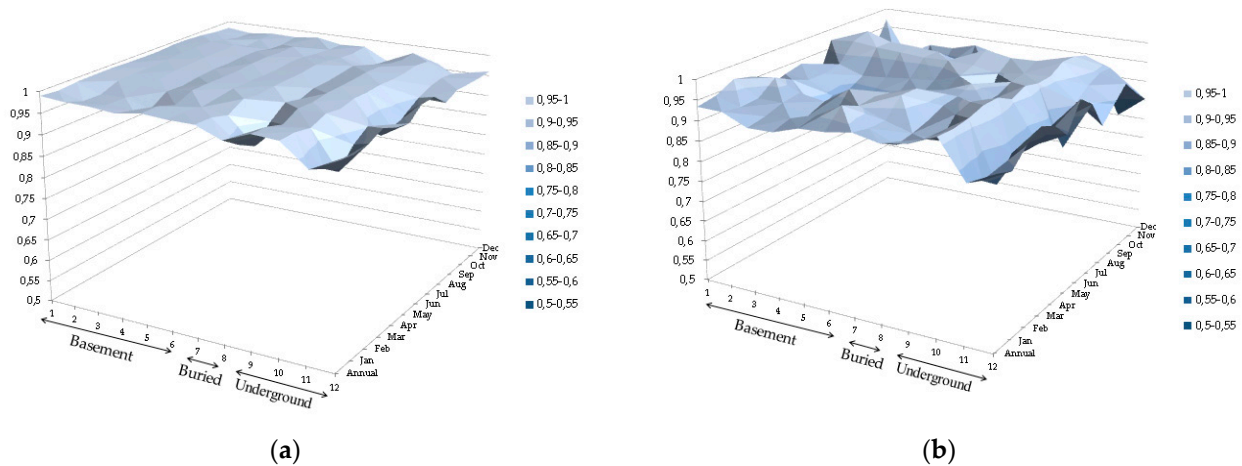


Figure 7. Temperature damping in the buildings analyzed (a) Mean daily temperature damping; (b) Mean monthly temperature damping.

In terms of relative humidity, in most aging rooms there are large variations throughout the year (Figure 8a,b), which denotes the inability of buildings to cope with outdoor humidity variations. In general, buried and underground constructions have an internal relative humidity higher than the exterior, with an annual average above 90% r.h. Basements maintain relative humidity values closer to the external average (Table 2). Despite this, the annual damping of relative humidity is very variable, with an average of $51 \pm 16\%$ r.h., ranging from 27% (warehouse 8) to 75% (warehouse 9). Monthly and daily damping is also moderate, with an average of $72 \pm 4\%$ r.h. and $85 \pm 7\%$ r.h. respectively due to the high hygroscopicity of the materials used in the wineries which implied high humidity inertia.

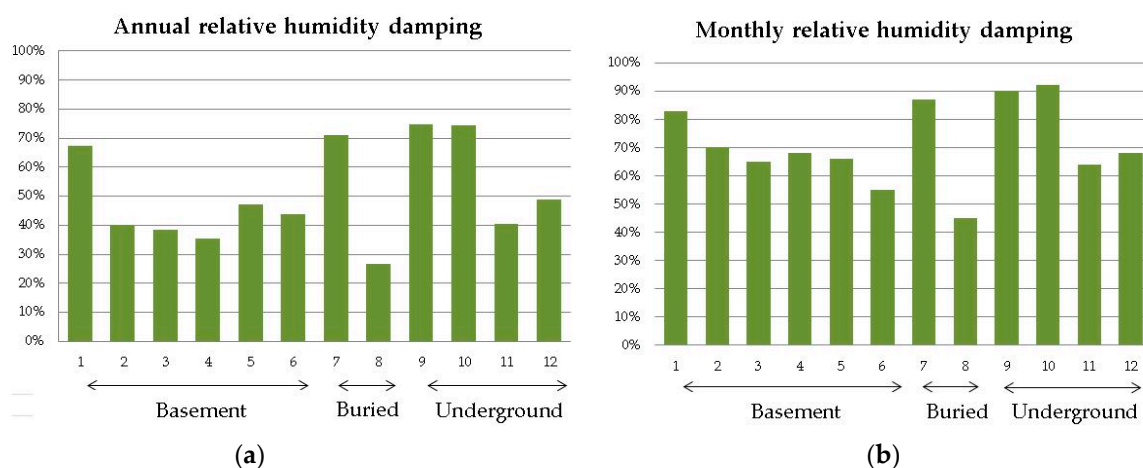


Figure 8. Damping of relative humidity in buildings analyzed (a) Annual relative humidity damping; (b) Monthly relative humidity damping.

Table 2. Representative values of the relative humidity inside each of the monitored aging rooms.

Typology	Average	Mean	Dev. Est.	Variance	Kurtosis	Coef. Asymmetry	Annual Breadth	Min	Max
1	84	84	5.6	31	−0.4	−0.4	35	60	95
2	82	83	9.7	93	−0.9	−0.3	55	45	100
3	73	73	8.8	78	−0.7	0.0	51	46	98
4	75	74	9.6	93	−0.7	0.1	55	43	98
5	76	75	7.8	60	−0.7	−0.1	43	47	90
6	73	73	10.0	99	−0.2	0.1	58	43	100
7	87	87	4.7	22	−0.6	−0.3	34	63	97
8	74	75	13.5	182	−0.8	−0.3	63	37	100
9	95	96	4.5	20	1.2	−1.1	27	73	100
10	97	100	5.5	30	4.0	−2.1	31	69	100
11	93	100	9.0	81	0.7	−1.3	54	46	100
12	92	97	10.1	103	−0.2	−1.0	50	50	100

These differences can be justified by the dependence on pressures generated by natural ventilation and the influence of outdoor climatic conditions. However, although such dependence could be assessed negatively, according to previous studies, its effectiveness in thermal and humidity control has been shown to be superior to that of mechanical ventilation in warm regions [46].

3.3. Cost

The warehouses analyzed have construction costs ranging between 42 €/m³ and 233 €/m³ (Figure 9), noting a large difference between basement warehouses whose average cost is 84 €/m³, buried warehouses whose average cost is 57 €/m³ and underground warehouses that have an average of 204 €/m³. The differences between them are due, first, to the conditions of execution. Although in the basement and the buried warehouses the accessibility of the machinery and the type of machinery to be used is more common, in the underground warehouses the specific conditions of accessibility of machinery together with their specificity results in a reduction of yields and an increase in the cost of execution.

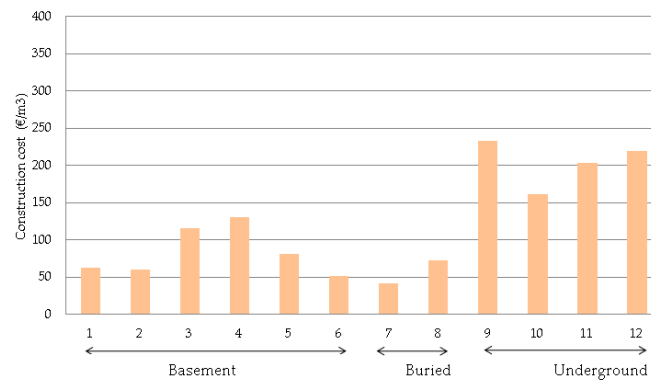


Figure 9. Construction costs associated with each of the analyzed warehouses.

Indeed, from the study of the cost of the warehouses, two large groups emerge, namely underground buildings in which the impact of excavation is clearly significant compared to basement or buried buildings, in which the civil works necessary for guarantee security conditions during construction and speed of execution are more important (Figure 10). Thus, compared to the average 77% of underground in the case of the impact of the excavation, this percentage is reduced to 16% in the case of basement warehouses and 12% in the case of buried ones. This is mainly because basement and buried warehouses are, commonly, of new construction, and both the type of machinery to be used and its accessibility to the excavation point are simpler than that of the traditional underground warehouses. Also, the access of the machinery in these two typologies is carried out taking advantage of uneven ground or, in some cases, emptying and subsequent filling with ground, which substantially simplifies the execution and, therefore, the cost. However, in the underground warehouses, especially in the traditional ones, the execution should be done, in most cases, lowering the machinery through a forklift, which would slow down the execution processes and, at the same time, substantially limit the type of machinery to be used, thus not allowing the optimization of the execution, and increasing the cost.

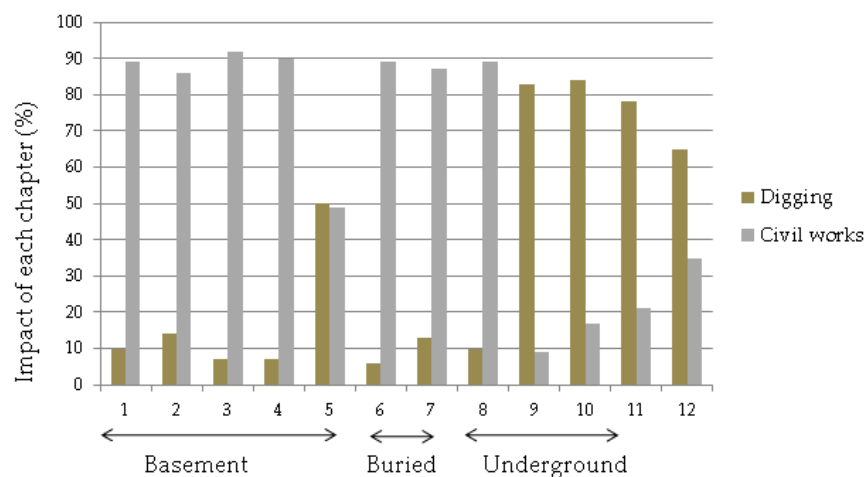


Figure 10. Construction costs by chapter associated with each of the analyzed warehouses.

Likewise, this difference in terms of the construction process of the warehouses justifies the difference found in the impact of the civil works of both (Figure 10). Compared to 82% on average of the total cost of execution in the case of basement warehouses and 88% for buried warehouses, this percentage is considerably reduced to 21% on average in the case of underground warehouses, due to the fact that in the latter, civil works are limited to the execution of reinforcements when needed. In the latter case, despite the low impact they have on volume, their impact on the overall cost is high due to the use of traditional

techniques that at current costs, require specialized labor (placement of stone factory or brick) and with a high impact on the overall cost.

As for the installations, it is striking that the cost of these ranges from 0.03% to 8% in the case in which more forklifts have been installed, which is in accordance with Worrell's maxim [30]. According to this maximum one of the effects of energy efficiency of the building implied the reduction of the expenses due to installation, maintenance and use (electricity and fuel consumption) and, consequently, the production costs as a whole.

3.4. Cost Analysis—Effectiveness

Beyond the individual costs of each type of warehouse, the main objective of the research is the evaluation of cost-effectiveness. For this purpose, it is necessary to consider the cost in relation to thermal damping and with humidity damping (Table 3).

Table 3. Average of cost, thermal, and humidity damping in the basement, buried, and underground typologies.

	Basement	Buried	Underground
Cost (€/m ²)	84 ± 32	57 ± 21	204 ± 31
%Annual thermal damping	78 ± 5	85 ± 5	84 ± 5
% Annual relative humidity damping	45 ± 11	49 ± 15	60 ± 20

If we compare the cost of each of the groups with the annual thermal damping, it is observed that the underground and buried warehouses have damping of approximately 85% on average while the former, with an average cost of 204 €/m³, triple the cost of the latter (57 €/m³). Basement warehouses with annual thermal damping temperatures of 78% on average have an average cost of 84 €/m³. Therefore, among the warehouses studied, we must highlight the buried warehouses, which are characterized by having a lower cost than the basement warehouses and, their thermal damping is similar to underground warehouses, with values of 85% and 93% for annual and monthly thermal damping, respectively. In terms of thermal operation this can be explained by the high thermal inertia granted by the land, while in economic terms the construction process of this type of warehouses presents higher work yields compared to that carried out in underground warehouses, in which the accessibility of the machinery determines and substantially increases the construction process.

Just as in the case of thermal damping, the damping of relative humidity also shows a clear relationship with the type of warehouse. Thus, the average annual damping is 45% in the case of basement warehouses and 49% for buried warehouses, compared to 60% of average damping in underground warehouses. However, in the case of underground warehouses, as well as buried warehouses, it should be noted the high dispersion of results in this parameter, with damping ranging between 41% and 75% in the underground, or 27% of warehouse 8 compared to 71% of warehouse 7, both being buried. This dispersion in the relative humidity results is a consequence of the number of ventilation points in each of them, observing that the greater the number of ventilation points, the lower the temperature damping reached in the warehouse.

If the buildings are analyzed individually, it is observed a large variation within each typology (Figure 11). This allows a conclusion that with a correct design, the differences between different typologies can be reduced or even non-existent since they depend on many parameters, such as the type of soil, topography, ventilation rates, etc.

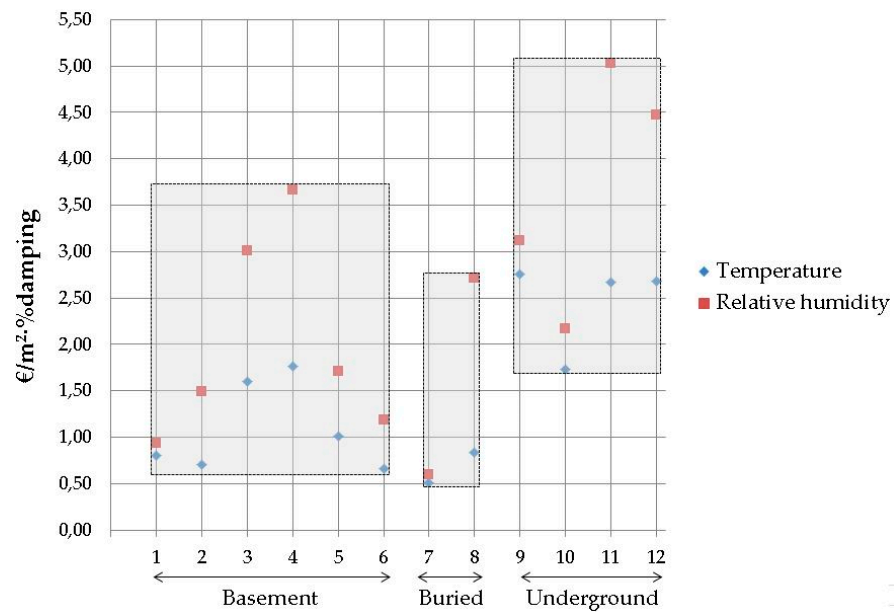


Figure 11. Correlation between cost and temperature and relative humidity.

4. Conclusions

The wine sector is no stranger to the requirements of reducing energy consumption that the European Union requires of buildings, and which, in this case, involves reducing the intensive use of energy in cooling and ventilation to obtain quality wine. Against this backdrop, basement, buried, and underground warehouses offer an alternative for optimizing indoor conditions with virtually no energy consumption, except that associated with the use of lighting or the transport and lifting of goods. Our study has the aim to analyze the correlation between the energy performance and the cost of constructive solutions that do not use air conditioning systems and that make quality wines to promote the design of zero-energy warehouses. To assess the relationship between the interior conditions and the cost of their construction, research has been focused on the analysis of the interior conditions and the cost associated with the construction of 12 wineries belonging to the types of basement, buried, or underground, which do not use mechanical systems for their conditioning and produce quality wines.

The research method used in the investigation is based on monitoring the temperature and humidity of the selected warehouses that, together with the economic data from the construction cost update, determine a parameter that has been called “construction effectiveness”. This parameter allows the evaluation of the cost–benefit ratio of each of the analyzed constructions.

According to the results of the research, these nearly zero-energy buildings passively provide, i.e., without the use of mechanical systems, great internal thermal stability with daily temperature variations below 0.2 °C/day. Except in special cases where, as a result of the high number of natural ventilation chimneys, this value can reach 1 °C during the summer months. Relative humidity presents greater fluctuation, with daily variations that can reach 9% r.h, although the averages range between 1–5% r.h. In this sense, it has been observed that the construction design strongly conditions the interior hygrothermal environment, there being important differences between the different warehouses. Solutions in basement (warehouses 1 to 6) and buried (warehouses 7 and 8) have a higher maximum annual temperature (>16 °C) and average temperature (>13 °C) compared to underground solutions (warehouses 9 to 12) with maximum < 16 °C and average < 13 °C. Therefore, this underground typology is the constructions with the greatest thermal inertia. In addition, basements also have, in general, lower average relative humidity. Therefore, the particular

requirements imposed by a winemaker to carry out the aging of a quality wine, could condition the selection of a certain type of zero-energy building.

In any case, it can be concluded that the zero-energy buildings analyzed have a great effectiveness in damping the temperature variations of the outdoor environment. Annual thermal damping exceeds 73% in all analyzed buildings, with an average of $81 \pm 4\%$. Constructions increase their effectiveness on a monthly and daily scale, with an average of $93 \pm 2\%$ and $98 \pm 1\%$ respectively. Except for buildings with high ventilation, the effectiveness increases as the thermal inertia of the solution used increases, with buried and underground constructions being more effective than basements. In terms of relative humidity, however, the buildings analyzed have high relative humidity that, on average, range from 73% to 97% which is strongly conditioned by various factors such as ventilation.

Regarding the cost of construction, the items with the greatest impact are excavation (including earthworks) and civil works, with a clear difference depending on the type of warehouse. In the underground, the impact of the excavation amounts to 77% of the total construction cost due to the penalty of the type of machinery required for the execution of reduced sections and, mainly, of low accessibility. This percentage, however, is reduced to 16% in the case of basement warehouses, in which, however, the impact of civil works is higher and amounts to 82%. The latter percentages are very similar to the case of buried warehouses, in which the impact of civil works is 88% and that of excavation 12%. Although the cost per cubic meter executed may be higher than the superficial warehouses, the absence of air conditioning and ventilation equipment and the passive operation of the building means a considerable reduction in the overall production costs associated, not only with the installation, but also with the maintenance and use of the systems.

Finally, the correlation between the indoor environment achieved by each warehouse and its construction cost, allows a conclusion that there is a large variation among the analyzed warehouses. Thus, to achieve each percentage of damping improvement, the average cost ranges from 0.5–2.7 €/m² for temperature and 0.6–5 €/m² for relative humidity. The average cost is 0.7 ± 0.2 €/m² for buried warehouses, 1.1 ± 0.5 €/m² for basement warehouses, and 2.5 ± 0.5 €/m² in the case of underground warehouses. Nevertheless, with a correct design, the differences between different typologies can be reduced or even non-existent. In this sense, the suitability of the construction system will be defined according to the grape management practices and the specific production needs.

There are two main limitations in this research. The first one relates to budgeting: there is a widespread lack of uniformity, and, in certain occasions, aesthetics are more important than efficiency in construction. The second one derives from the lack of homogeneity of criteria found among the oenologist for the definition of the “optimal” internal conditions, which prevents us from obtaining more specific conclusions.

The research carried out indicates that further analysis can be performed increasing the number of wineries of each typology, with the same ratio of ventilation—which was found to be very influencing in the performance—to find a correlation between the different parameters such as placement, type of soil, type of grapes, and depth of winery, among others.

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