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Research Article

Techno-Economic Feasibility of Solar Water Heating Systems in the Winemaking Industry

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The present work analyzes the feasibility of using solar water heating systems (SWHS) to supply the hot water required in the winemaking industries. The hot water demand of the sector was characterized by selecting patterns that encompass the wide range of existing casuistry. After determining the production potential of the SWHS by using an experimental system, 22500 energy simulations were carried out, combining different locations, energy prices, and prices of the necessary investment. The results demonstrate that the seasonality and irregularity of a winery's demand pattern drastically condition the viability and profitability of SWHS. In wineries with high demand, which are relatively uniform throughout the year, the solar system with optimized design achieves energy consumption reductions between 32% (low radiation) and 52% (high radiation), with payback between 4.3 and 7.2 years. On the other hand, in wineries with highly seasonal consumption, SWHS are not profitable even in very favorable cases.

1. Introduction

The world wine industry generates billions of euros per year, thanks to the production of over 250 million Hl in recent years [1]. Within the European Union, wine stands as the foremost export product in the food and beverage sector, commanding a value exceeding 16 billion euros, nearly twice that of the second-ranking product on the list [2]. The economic importance of the sector, together with its high energy demand and the increase in energy prices, makes it necessary to improve the energy efficiency of wineries and to promote renewable energy sources.

Despite their significant global growth, solar water heating systems (SWHS) have seen limited implementation in wineries due to factors such as low energy prices and the irregularity of demand. However, the increase in energy bills over the last two years raises the need to analyze their viability in the new energy context, taking into consideration the particularities of the hot water demand in the wineries.

1.1. Hot Water Consumption in the Winemaking Industry. The use of water is necessary in practically all cleaning processes carried out in wineries. There are various cleaning methods, the most common being brushing, spraying, circulation, and CIP (cleaning-in-place). High-temperature water is mainly used in filter cleaning, bottling, barrel washing, and yeast rehydration.

Before bottling the wine, amicrobic filtration is carried out with membrane filters. The usual pore size of these membranes is 0.45 μm to retain bacteria and 0.65 μm to retain yeasts. According to Togores [3], the filter cartridges must be sterilized with water at 80°C before and after filtration, using a water flow rate of at least one-third of the liquid to be filtered for 30 minutes. To use less water, it can be recirculated back to the pump suction. The recommended cleaning protocols vary according to the cartridge suppliers (InVia, Pall, Agrovin, etc.), with temperatures between 80 and 90°C and a minimum time of 10 minutes if prior washing with water at room temperature is carried out. Disinfection can also be performed with steam.

Hot water consumption in tangential filters depends not only on the volume of wine filtered, but also on other factors such as the filter model, the filtration surface, the type of product (viscosity and solid particle content), or the previous clarifying treatments carried out on the wine. For this reason, manufacturers' recommendations vary widely. For example, the recommended volume for a cleaning cycle of a specific supplier (Della Toffola) can vary from a few tens to hundreds of liters depending on the size and model of the filter. The maximum temperature also varies from 60 to 70°C depending on the supplier (Romfil, Pall, Bucher Vaslin, etc.).

Different types of equipment can be used for barrel disinfection depending on the number of barrels to be washed, including multidirectional flexible washing heads with suction, manual barrel washers, and semiautomatic barrel washers. The volume and temperature required vary according to the pressure and capacity of the equipment. Temperature ranges are between 50 and 90°C (and steam at 130°C). The volume required per barrel is usually between 60 and 100 liters.

The dry yeast rehydration protocol for preparing the vat food is key to ensuring a viable and active population for alcoholic fermentation. Most suppliers (Vinqualis, Larroque Oenologie, Agrovin, etc.) recommend similar values of temperature and volume of water: 20–30 g of yeast per Hl of wine, rehydrating it in 10 times its weight of warm water (35–40°C).

1.2. Hot Water Supply via SWHS. At the industrial level, there are numerous scientific papers studying solar thermal systems in various processes and applications. Several recent reviews have been published [4–7].

According to Ismail et al. [8], industrial heat demand can be classified into three categories: low-temperature thermal utilisation (below 80°C), medium-temperature thermal utilisation (80–250°C), and high-temperature thermal utilisation (above 250°C). The low-temperature range is used in food and beverage industries mainly for blanching, scalding, smoking, tempering, washing, and cleaning. Meanwhile, the medium-temperature range is used for pasteurising, sterilising, hydrolysing, and drying. Therefore, the necessary solar systems in wineries can mainly be classified as low-temperature systems.

There is no evidence of previous work analyzing the feasibility of SWHS in wineries, unlike other types of agro-industries such as the meat industry [9, 10], dairy industry [11], and soft drinks industry [12]. These studies highlight the significant variations in profitability and feasibility that occur depending on the location, context, and demand pattern. Therefore, considering the vast variability in winery sizes, the disparity in activity planning, and the diverse irradiation across locations, it is necessary to carry out an analysis adapted to the peculiarities of the sector.

Furthermore, recent studies have demonstrated that the new energy context brings significant shifts in the feasibility and profitability of thermal solar systems in other agro-industries. Thus, for example, in the meat industry, paybacks ranging from 7 years to more than 20 years were obtained by considering energy prices from 2012 to 2016 [10]. When analyzing the same case with 2022 energy prices, the payback is reduced to less than 4 years [13]. Equivalent results have been obtained for photovoltaic systems in wineries [14, 15]. It is imperative to conduct targeted studies of SWHS in wineries tailored to the current context and its price volatility.

Therefore, the main objective of this study is to provide a comprehensive overview of the feasibility and profitability of thermal solar systems in wineries, considering the new energy context, as well as the specificities and diverse scenarios present within the sector.

2. Materials and Methods

To achieve this objective, a characterization of hot water consumption in wineries was conducted, selecting three markedly different usage patterns. Considering that wineries require water up to 90°C, it was necessary to characterize the performance of an experimental SWHS to produce water at high temperatures. Subsequently, a tool for energy and profitability calculation was developed, enabling the evaluation of SWHS implementation across a wide array of scenarios. Specifically, the study examined 225 scenarios, each encompassing 100 different SWHS sizes (Figure 1).

The main limitation of the proposed methodology when assessing the viability of a SWHS in a specific winery lies in estimating the demand for hot water for each hour of the year. The energy calculation tool is based on SWHS utilizing evacuated tube collectors (deemed most suitable for the required temperatures), and its accuracy has not been characterized for flat collectors.

2.1. Hot Water Consumption Pattern. The water consumption of wineries has been extensively characterized, showing variations of several liters per bottle depending on the size and involved processes [16–18]. However, there is no record of articles or technical documents characterizing the hot water consumption of wineries beyond the data provided by manufacturers or some oenological treaties described previously.

The pattern of hot water consumption in wineries varies enormously due to several factors: wineries with large production tend to use tangential filters, while others filter using procedures that do not require hot water; the demand for filtration varies enormously according to the type of wine filtered; the winemaker's requirements and the previous treatments; the time and frequency of filter cleaning that vary greatly depending on the manufacture; and the habits and criteria set by the winemakers. In wineries with large production, consumption tends to be much more uniform and higher than in small wineries.

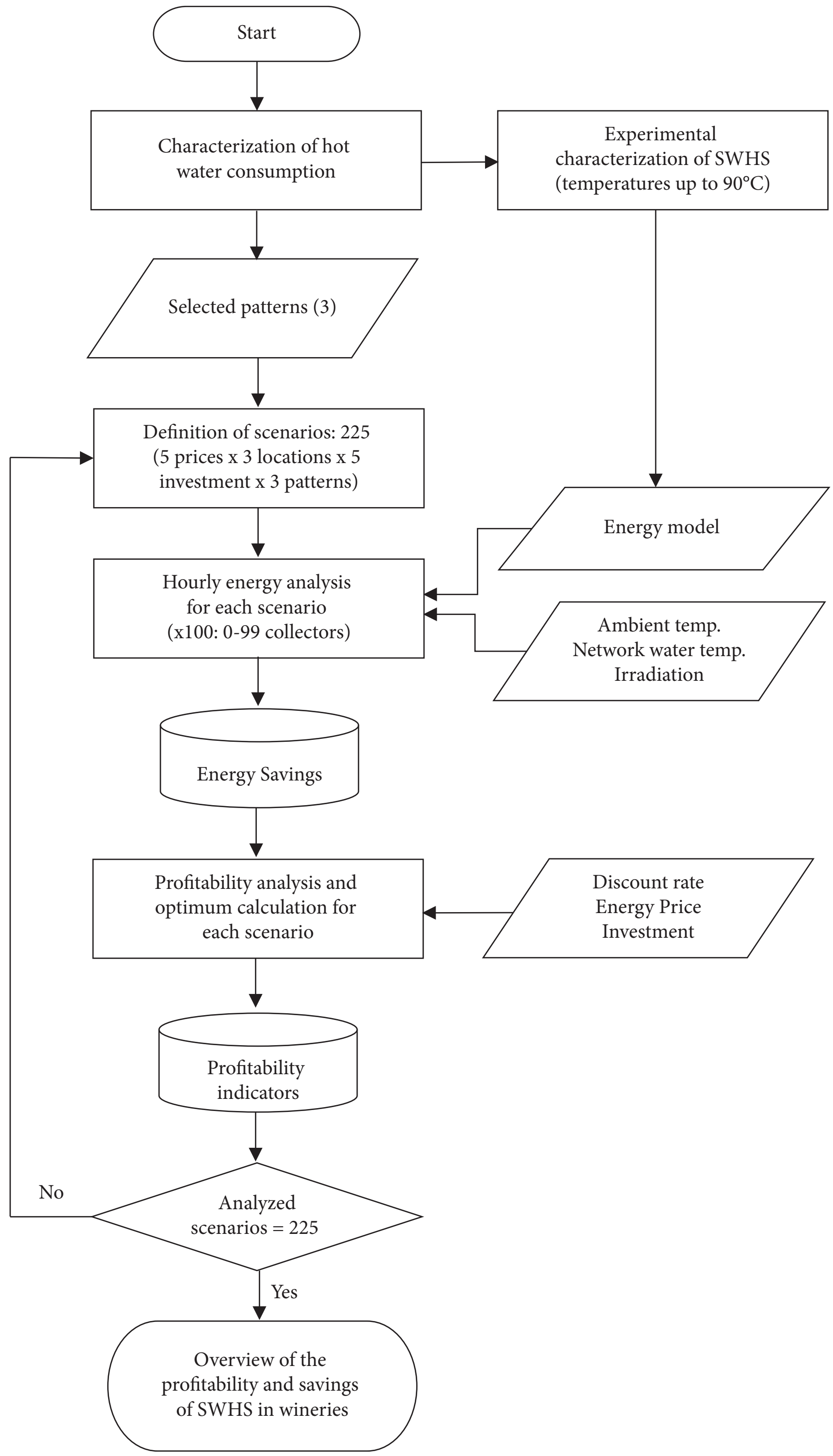


Figure 1: Methodology flowchart.

After characterizing the consumption pattern of numerous wineries in Spain and Portugal, and taking into account the differences in the size of the wineries in the main wine regions of the world [19, 20], 3 patterns have been selected that would cover a large part of the existing casuistry (Figure 2). Two scenarios can be regarded as extremes: one depicts a large-scale winery characterized by substantial and moderately consistent demand, while the other involves a small winery with limited and highly seasonal demand. The third scenario portrays the consumption pattern typical of a medium-sized winery in specific countries.

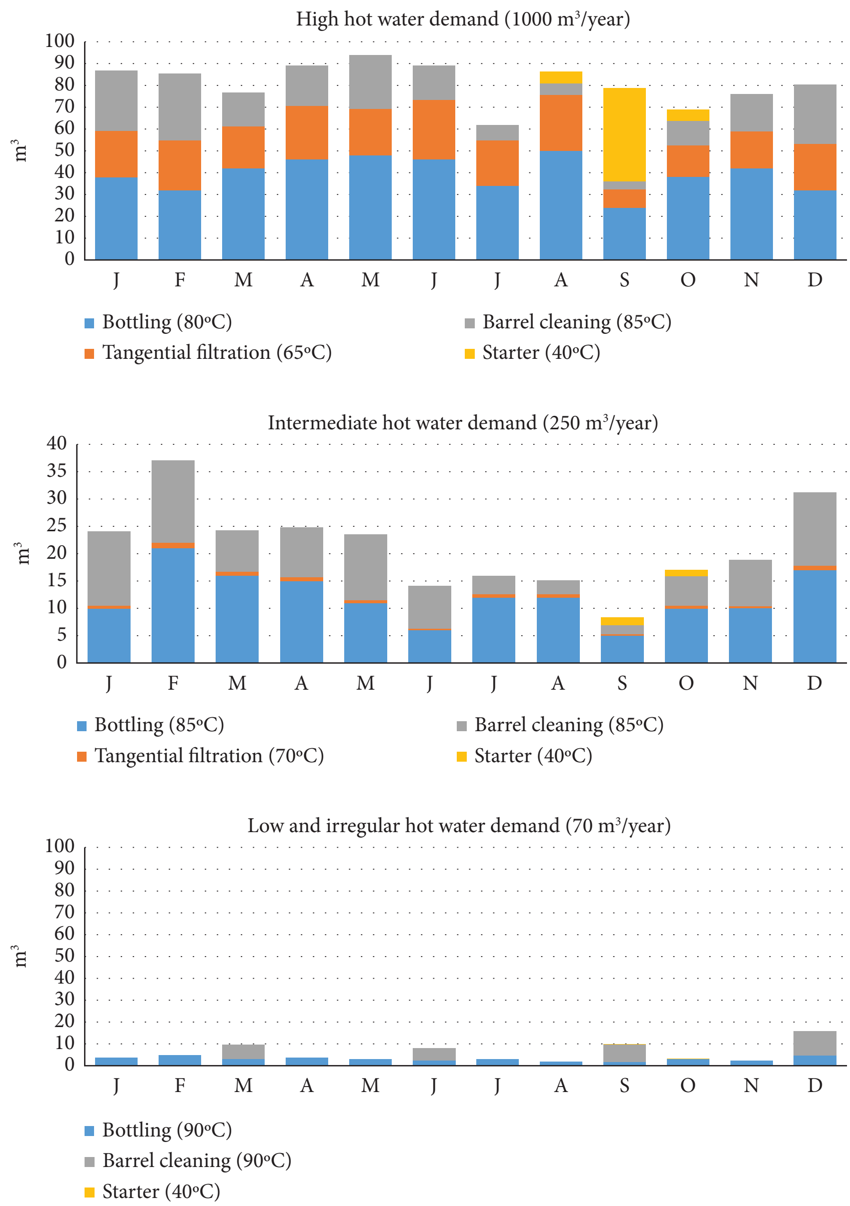


Figure 2: Monthly hot water demand of the three patterns analyzed.

2.1.1. Pattern 1: High Hot Water Demand (Close to 1000 m^3/Year) Relatively Uniform. This is a high-production winery, representative of large agri-food cooperatives in central Spain. Its annual hot water demand is close to 1000 m^3. It dedicates an important part of its production to the sale of wine in bulk, in this case, more than 70%. The work is distributed in 3 shifts of 8 hours, from Monday to Friday. Hot water is required for 268 days per year. Therefore, on 27% of the days, primarily most weekends throughout the year, hot water is not demanded.

Bottling is carried out for an average of 20 ± 4 days per month, with monthly variations due to batches and the type of wine requested by large customers. The cleaning of the bottling machine, which requires hot water, is typically carried out in the early hours of the morning and at the end of the bottling shift, by using water at 80°C and a volume close to 2,000 liters.

All the bottled wine and about 30% of the bulk wine are filtered with a tangential filter. Filtration is carried out during consecutive working days according to the needs of the month, with an average of 12 ± 3 days. Hot water at 65°C is required for cleaning the filter on days when filtration takes place, with cleaning sessions typically scheduled in the early morning, afternoon, and evening.

Only a small part of the production, close to 1%, is aged, with about 10130 barrels. The barrels are cleaned continuously for a few hours per month (average 15 ± 8 hours per month), using approximately 60 liters of water at 85°C per barrel.

During the harvest season, a starter is prepared for approximately 30% of the total production, requiring 0.0025 liters of water at 40°C for every liter of wine fermented with tank yeast.

2.1.2. Pattern 2: Intermediate Hot Water Demand (250 m^3/Year). Demand patterns correspond to a medium-sized winery in countries such as the USA (California) or Australia. This is a winery with an average annual consumption of hot water of around 250 m^3. In this winery, the number of days requiring hot water reduces to 212 (42% of the days in the year without demand). It has a production of 1 million liters of wine that it sells bottled. The work is usually carried out in 1 shift of 8 hours, without hot water consumption during weekends. Bottling is carried out depending on demand, with an average of 11 ± 5 days per month. Cleaning is carried out before and after bottling, requiring approximately 1000 liters of water at 85°C for each cleaning.

Tangential filtration is carried out during consecutive working days according to the needs of the month, with an average of 8 ± 3 days per month. Filter cleaning is carried out with water at 70°C, being usual at the end of filtration. Barrel cleaning is carried out continuously in a few hours per month (average of 6 ± 3 hours), using approximately 75 liters of water at 85°C per barrel. All the wine is fermented with commercial yeasts using 0.0025 liters of water at 40°C per liter of wine.

2.1.3. Pattern 3: Low and Irregular Hot Water Consumption (70 m^3/Year). This is a winery with an average annual consumption of hot water of around 70 m^3. All of its production is bottled. The work is carried out in 1 shift of 8 hours, from Monday to Friday, with the possibility of increasing the hours during the grape harvesting season. Hot water is only required for 70 days a year, accounting for an 81% lack of demand.

Given the low production, the winery does not have a tangential filter. It has a bottling machine that uses water at 90°C for cleaning (5 ± 2 days per month), carried out before and after bottling, with a total volume close to 600 liters daily. The barrels are cleaned in one day every quarter (average of 7 ± 2 hours per month), using 90°C water. All the wine is fermented with commercial yeasts using 0.0025 liters of water at 40°C per liter of wine.

2.2. Scenarios Analyzed. In order to draw global conclusions on the feasibility of SWHS in wineries, 225 scenarios have been considered. Each of the 3 consumption patterns has been analyzed in 3 different locations, considering 5 energy prices and 5 prices of the necessary investment. In order to determine the optimal sizing of the SWHS, for each of the scenarios, 100 different sizes of the solar system have been calculated.

2.2.1. Locations. Most wine production regions have an irradiation between 3 and 5 peak sun hours (PSH, equal to 1000 W/m^2 of sunlight per hour). Thus, for example, Bordeaux has 3.4, Cagliari has 3.7, Napa has 4.8, areas near Melbourne and Canberra have around 4.8, and in the vicinity of Santiago de Chile, it is 4.9. For this reason, two locations of extreme value (PSH 3.0 and 5.0) and another of intermediate radiation (PSH 4.0) have been selected, all of them with a long winemaking tradition in three of the countries with the highest world production, specifically, San Diego (5.0), Montpellier (4.0), and Stuttgart (3.0). Irradiation data (with tilt angle equal to latitude), ambient temperature, and water temperature from the supply network (assuming equivalent to the ground temperature at 0.5 m) have been extracted from the EnergyPlus climatological files (Figure 3), in particular, USA_CA_-San.Diego-Lindbergh.Field.722900_TMY.epw (PSH 5.0), FRA_Montpellier.076430 _IWEC.epw (PSH 4.0), and DEU_Stuttgart.107380_IWEC.epw (PSH 3.0).

For the calculation of heat losses with the environment, it has been assumed that the water tank will be located in the interior space of a warehouse. The interior temperature has been calculated by using a simulation model developed and validated in a previous work [21], by using the climatological files of each location.

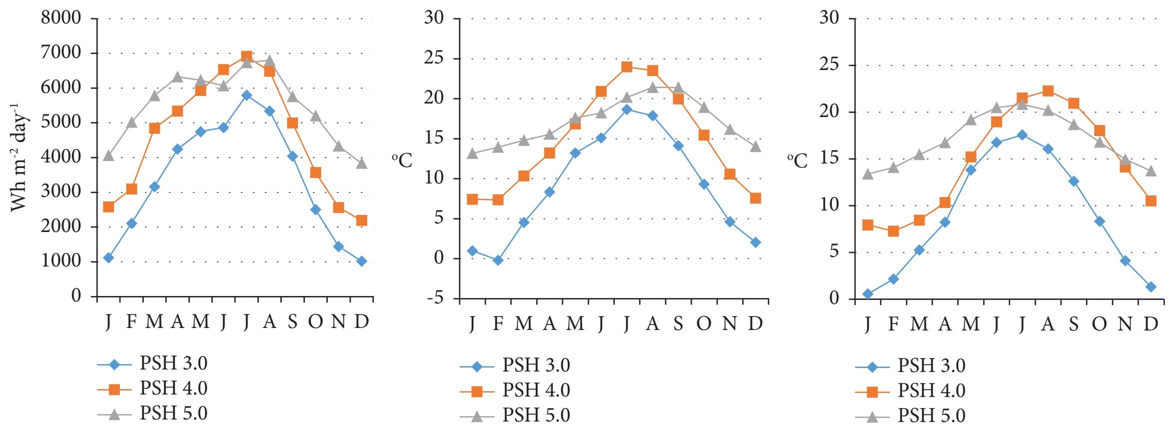
2.2.2. Energy Prices. Taking into account the great instability and variability of prices currently existing, the study will analyze a wide range, from 0.10 €/kWh (situation close to the price before the war in Ukraine) to 0.50 €/kWh (price reached in some wineries in 2022), with an interval of 10 cents. For simplification of results, a single price is assumed regardless of the type of supply (electricity, gas, and diesel).

2.2.3. Investment. The investment required to implement a SWHS varies significantly based on variables such as the collector model and surface area, roof inclination, labor costs in the country, and component manufacturer. For instance, according to CYPE's price database in Spain [22], considering the same collector model, the investment decreases from 815 €/m^2 for 2 m^2 to 675 €/m^2 for a 4 m^2 collection area. Given the great variability of prices, a wide price range of the investment required for industrial facilities will be analyzed, from 500 €/m^2 to 900 €/m^2, with a range of 100 €/m^2.

2.3. SWHS Energy Analysis

2.3.1. Characteristics of SWHS. The energy analysis was based on an experimental SWHS with a vacuum tube collector and active circulation. The performance of the evacuated tube collectors (ETCs) is better than that of flat plate collectors (FPCs), especially in cold climates [23]. In addition, ETC allows higher temperatures to be reached [24, 25]. In 2021, 60% of the thermal power installed corresponds to SWHS with ETC [26].

The experimental SWHS was used in previous work [10, 24, 25, 27, 28]. Its programming was modified to produce water at temperatures of up to 90°C (from 40°C in 10°C intervals), in 6-day cycles. It has a collection area of 2 m^2 and a tank of 80 L (Figure 4). For one year, the numerous sensors installed characterized the system energetically, using the data to validate an energy performance model.



(a) Solar irradiation (b) Ambient temperature (c) Network water temperature

FIGURE 3: Irradiance on the tilted surface of the collector (a), outside air temperature (b), and temperature of the water coming from the supply network (c). Monthly averages for each of the locations with different radiation (3.0, 4.0, and 5.0 peak sun hours, PSH).

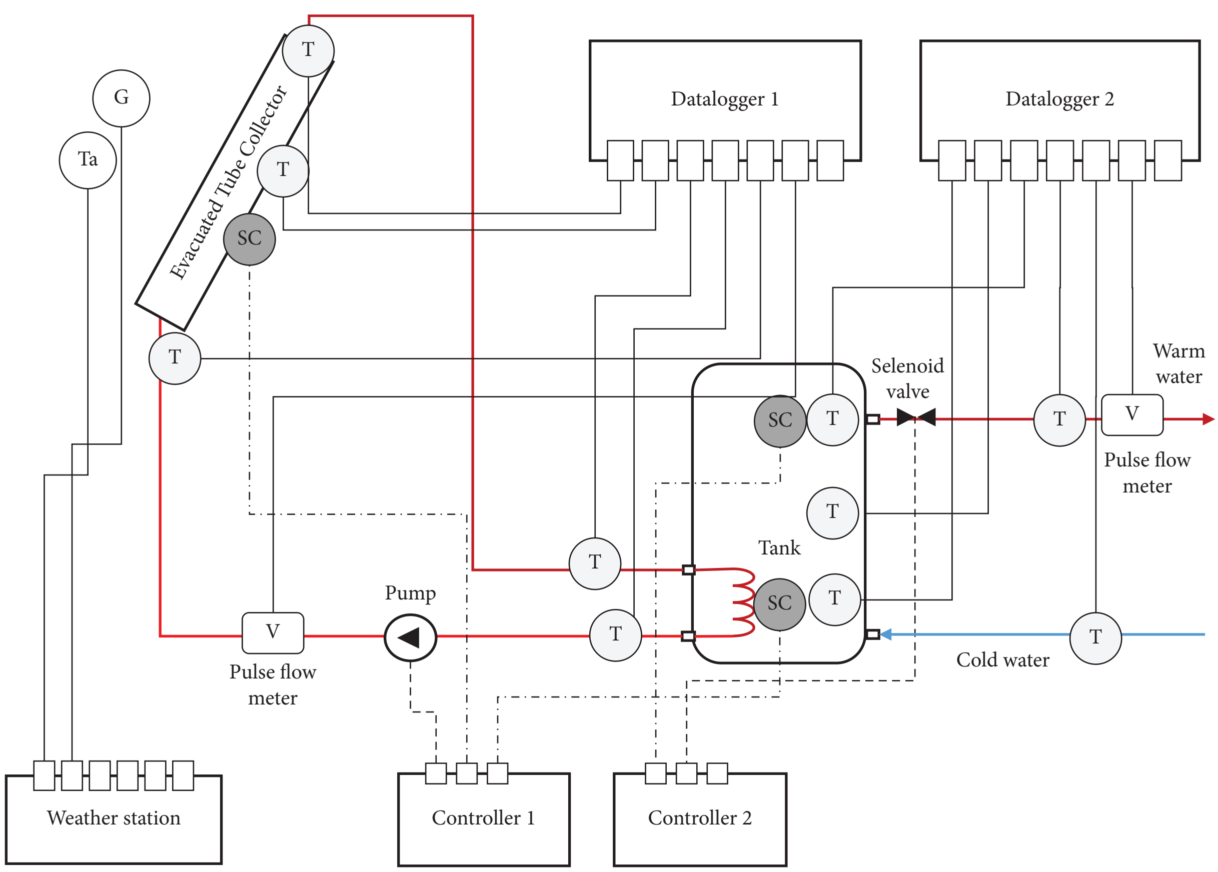


FIGURE 4: Main components of the experimental SWHS.

2.3.2. Energy Simulation. The energy simulation is based on a model estimating the useful energy that the experimental SWHS is able to store in the tank (Q_{SWH}, W·m^{-2}), and which has already been used and validated in previous work in the meat industry [10]. This energy is calculated from irradiance (G, W·m^{-2}), ambient temperature (T_a, °C), and the water temperature in the tank (T_t, °C), according to equation (1), with η_{0S} being the zero loss efficiency of the SWHS (dimensionless), a_{1S} the first-order heat loss coefficient (W·m^{-2} °C^{-1}), and a_{2S} the second-order heat loss coefficient (W·m^{-2} °C^{-2}). The monitoring data obtained during one year, with temperatures up to 90°C, were used to calculate the constants of the equation. Using the Microsoft Solver optimization tool, constants were obtained that minimized the difference between the energy calculated with the model and the actual energy released to the tank, calculated from the sensor data ($R^2 = 0.994$, typical error 279 Wh·m^{-2}·d^{-1}).

$$Q_{\mathrm{SWH}} = \eta_{0S}G - a_{1S}\left(T_t - \mathrm{T_a}\right) - a_{2S}\left(T_t - T_a\right)^2 = 0{,}7551G - 43{,}2053\left(T_t - \mathrm{T_a}\right) - 0{,}2905\left(T_t - T_a\right)^2. \quad (1)$$

For each of the 22500 cases analyzed, an individualized energy analysis was carried out. The energy variations experienced in the tank during the 8760 hours of the year and their effect on the water temperature were calculated. For this purpose, an improved version of a simulation tool developed with VBA (Visual Basic for Applications) programming in Microsoft Excel was used, which had been validated in previous works [10].

For each hour, the energy transferred to the tank from the collectors was calculated from the model (equation (1)). To do this, the energy obtained from the model was multiplied by the total collector surface area of the case analyzed.

In turn, in each hourly interval, the energy loss through the tank surface has been calculated. For this purpose, the same reference frame has been assumed for all cases: tank losses of 1.2 kW/24 h according to DIN 4753/8 (at 65°C and outside at 20°C); the tank is located inside a typical warehouse, whose interior temperature has been calculated by simulation, as described in a previous section. In this framework, the losses have been calculated by multiplying the temperature difference (tank water and ambient temperature) by the thermal transmittance of the tank insulation and by the surface area of the tank.

Finally, in the hourly intervals in which hot water was demanded, the energy extracted and its effect on the temperature of the water in the tank were calculated. The starting point is the energy demanded, multiplying the volume required by the temperature difference between the water demanded and the temperature of the water in the supply network. If the demanded temperature is higher than the tank temperature, the demanded volume is extracted (with a limit of the tank volume), being the remaining energy (necessary to reach the required temperature) provided by the conventional supply system. Conversely, if the demanded temperature is lower than the tank temperature, the volume withdrawn is reduced by mixing with cold water. The energy supplied by the conventional system is also calculated as the difference between the energy demanded and the energy supplied by the SWHS.

Therefore, the temperature of the water in the tank (T_t) will change every hour according to the energy variations described above (ΔE, Wh), taking into account the volume of the tank (V_t, m^3), specific heat (Wh·kg^{-1} °C^{-1}), and fluid density (ρ, kg·m^{-3}).

$$T_{t,\mathrm{after}} = T_{t,\mathrm{before}} + \frac{\Delta E}{V_t \cdot \rho \cdot c_p}. \quad (2)$$

Once the energy balance is completed, the tool calculates the sum of irradiation, energy supplied by the solar system, total energy demanded by the winery, and energy supplied by the conventional system.

In order to calculate the reduction of CO_2 emissions, a value of 0.14 kg CO_2eq kWh^{-1} has been considered for the electricity supply, the average of the Spanish energy mix in 2021 and 2022. Equivalently, a value of 0.29 kg CO_2eq kWh^{-1} has been assumed for diesel, according to the data published by the Ministry for Ecological Transition and the Demographic Challenge of Spain for the year 2021.

2.4. SWHS Profitability. In order to compare the different scenarios, the following frame of reference was assumed: SWHS useful life, 20 years; discount rate, 1.5%; and annual maintenance cost, 2% of the investment.

For each of the 22500 cases, the simulation tool described above calculates the total cost of the energy bill over the lifetime of the installation (20 years). This takes into account the initial investment required, the cost of the annual bills, and the cost of maintaining the SWHS. Specifically, it has been calculated as the NPV (net present value), discounting the annual payments according to the discount rate. Equivalently, the cost of the reference case without SWHS has been calculated, obtaining the total energy savings as the difference between both values.

The annual payments for the reference case without SWHS have been calculated by multiplying the energy required to heat the demanded water (kWh) by the cost of energy (€ kWh^{-1}). For the SWHS case, the total energy demand includes the energy supplied by the conventional system that the SWHS has not been able to provide and the consumption of the system's pump. The difference in annual payments with and without SWHS has been used as an annual cash flow for the payback calculation.

The initial investment required has been calculated by multiplying the collector surface of the subscenario by the reference price of the installation (€·m^{-2}).

Based on the initial investment required and the annual savings achieved, the discounted payback has been calculated by using the following equation:

$$\mathrm{K} - \sum_{\mathrm{j=0}}^{\mathrm{j=PB}} \frac{\mathrm{R_j}}{(1+\mathrm{r})^{\mathrm{j}}} = 0, \quad (3)$$

where "*K*" is the initial investment, "PB" is the payback, "*R*" is the annual cash flow (annual savings achieved), and "*r*" is the discount rate.

Finally, as a reference indicator for the sizing of the SWHS, the "savings/payback" ratio has been calculated by dividing the total savings achieved during the lifetime of the installation (%) by the payback.

2.5. Optimized SWHS Sizing. The optimal sizing of each scenario was carried out by comparing the 100 subscenarios, from 0 to 99 collectors of 2 m^2. This wide range has been designed to find the optimum considering the demand of the large winery. Although in the other wineries it is clearly excessive, it has been decided to maintain the same methodology and casuistry analyzed, with the same programming code of the calculation tool regardless of the pattern. In addition, it has made it possible to analyze the variations in energy costs when oversizing the system and to establish an appropriate design criterion. In total, the energy analysis and profitability assessment were conducted for 22,500 cases.

The criterion adopted was to maximize the "savings/payback" ratio, selecting as the optimal subscenario the one with the highest value of this indicator. This ratio combines the objective of achieving a further energy bill reduction with a lower risk associated with the investment. By adopting this sizing criterion, the number of solar collectors required is reduced, especially in installations with higher demand and, therefore, the initial investment is required. It also increases profitability at the cost of giving up a small percentage of the energy savings achieved. Thus, for example, in the highest demand pattern (pattern 1), the average reduction is 6 ± 5 collectors (27 ± 10 installations) and 0.6 ± 0.5 years of payback, giving up only 1% of the total savings. On the other hand, the optimal number of collectors tends to be unified in a large number of scenarios, reducing uncertainty in the face of future variations in energy prices. For all these reasons, and given the current context of instability, it has been taken as a reference sizing criterion, as it reduces the risk assumed.

3. Results and Discussions

3.1. SWHS Sizing. Prior to the energy context shift, the low energy price, represented by the value of 0.10 €/kWh in this study, resulted in significant variations in the optimal size of the SWHS within a specific winery when other parameters underwent changes. This circumstance complicated the design and implementation of SWHS (Figure 5). However, with the increase in energy prices (exceeding 0.20 €/kWh), the proposed design criterion, maximizing the "savings/payback" ratio, allows for achieving a similar optimal size across a wide range of scenarios, regardless of other variables such as investment cost, rising energy prices, or even irradiation. In essence, the new energy context promotes the design of SWHS, making it less sensitive to changes.

However, SWHS systems are not always feasible within the new energy context. The optimal size is significantly influenced by the winery's demand pattern. When the demand is small and irregular, SWHS might not be viable or may have a reduced size in cases where it is viable. Conversely, in wineries with a relatively uniform high demand, SWHS may require substantial collection areas (Figure 5). Thus, with pattern 1, the size of the optimized installation reaches a maximum value of 25-26 collectors in most of the scenarios. This size is necessary to cover the energy needs required by the large volume of water and days of demand. The small difference in the maximum number of collectors between locations is a consequence of the variations in energy needs due to the temperature of the supply network and the ambient temperature inside the winery. In the most unfavorable cases (lower radiation and low cost of energy), the installation of the SWHS entails losses compared to the reference scenario without SWHS. With the optimized collector design, overall system efficiencies of $35 \pm 3\%$, $35 \pm 8\%$, and $34 \pm 13\%$ are achieved for 5.0, 4.0, and 3.0 PSH, respectively, considering the set of cases analyzed.

When water demand is reduced in both volume and frequency (pattern 2), the optimal size decreases considerably to maximum values of 8-9 collectors. Given the irregularity and lower frequency of water demand, the number of scenarios in which the size differs from the maximum increases, as well as the cases in which the SWHS does not achieve savings compared to the baseline scenario. The more irregular demand also causes the overall system performance to be reduced to $25 \pm 8\%$, $24 \pm 9\%$, and $20 \pm 12\%$ for 5.0, 4.0, and 3.0 PSH, respectively.

If the water demand decreases even more in frequency and volume (pattern 3), SWHS is no longer viable in most of the scenarios analyzed, even with high radiation and intermediate energy and investment prices. In the cases where savings are achieved, the installation is small, with 3-4 collectors. The low number of days of hot water demand hinders the overall efficiency of the system, thus wasting a large part of the incident radiation. Thus, the overall efficiency is 12% in all the scenarios in which it is feasible.

3.2. Reduction of Energy Consumption. The reduction in energy consumption achievable is closely linked to the uniformity of demand. In a large winery with relatively uniform consumption, higher percentages of savings can be achieved compared to a winery with more irregular demand. Furthermore, the significant irregularity in the small winery further diminishes the potential savings that can be attained in cases where the SWHS is feasible (Figure 6).

The higher energy prices in the new context lead to a significant increase in the percentage of savings achievable with SWHS. Similar levels of savings are reached from 0.20 €/kWh onwards in most scenarios, except in instances of low irradiation and/or highly irregular patterns (Figure 6). Thus, with pattern 1, the optimized solar system allows achieving energy consumption reductions close to 32% for PSH 3.0, 44% for PSH 4.0, and 52% for PSH 5.0 in more than half of the scenarios analyzed, starting at 0.20 €/kWh (Figure 6). The maximum savings percentage is somewhat lower than in agribusinesses with a more uniform pattern, where values around 60% can be achieved [13]. The implementation of SWHS in a winery with these characteristics would mean an average annual reduction in emissions of 4273 ± 1002 kg CO_2eq/year, 3602 ± 1170 kg CO_2eq/year, and 2589 ± 1175 kg CO_2eq/year for 5.0, 4.0, and 3.0 PSH, respectively. If the heating was carried out using a diesel boiler instead of electric water heaters, these figures would be doubled.

Considering pattern 2, the percentage of savings is reduced. In the PSH 4.0 and 5.0 scenarios, a maximum range of consumption reduction is reached in almost all scenarios from 0.30 €/kWh and in some from 0.20 €/kWh, specifically, between 32% and 35% for PSH 4.0 and between 38% and 42% for PSH 5.0 (Figure 6). In the case of PSH 3.0, maximum values between 21% and 25% are achieved in fewer cases, combining low investment prices and/or high energy prices. The implementation of SWHS in this winery would result in average annual emission reductions of 889 ± 363 kg CO_2eq/year, 793 ± 359 kg CO_2eq/year, and 468 ± 318 kg CO_2eq/year for 5.0, 4.0, and 3.0 PSH, respectively.

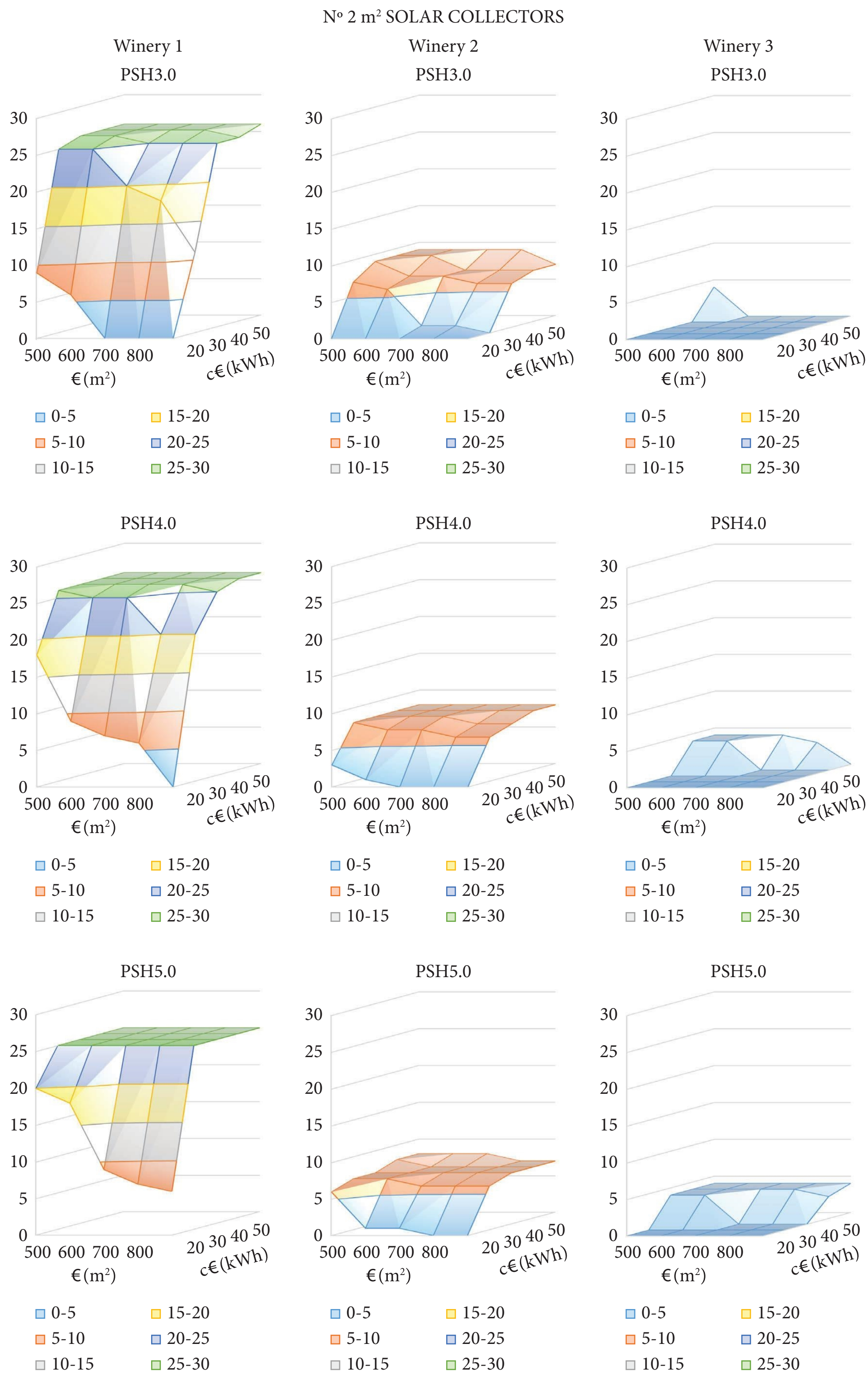


Figure 5: Optimized number of $2\,m^2$ solar collectors that maximizes the “savings/payback” ratio in the different scenarios analyzed.

Figure 6: Reduction in energy consumption (% kWh total) achieved by installing the optimally sized SWHS in the different scenarios analyzed.

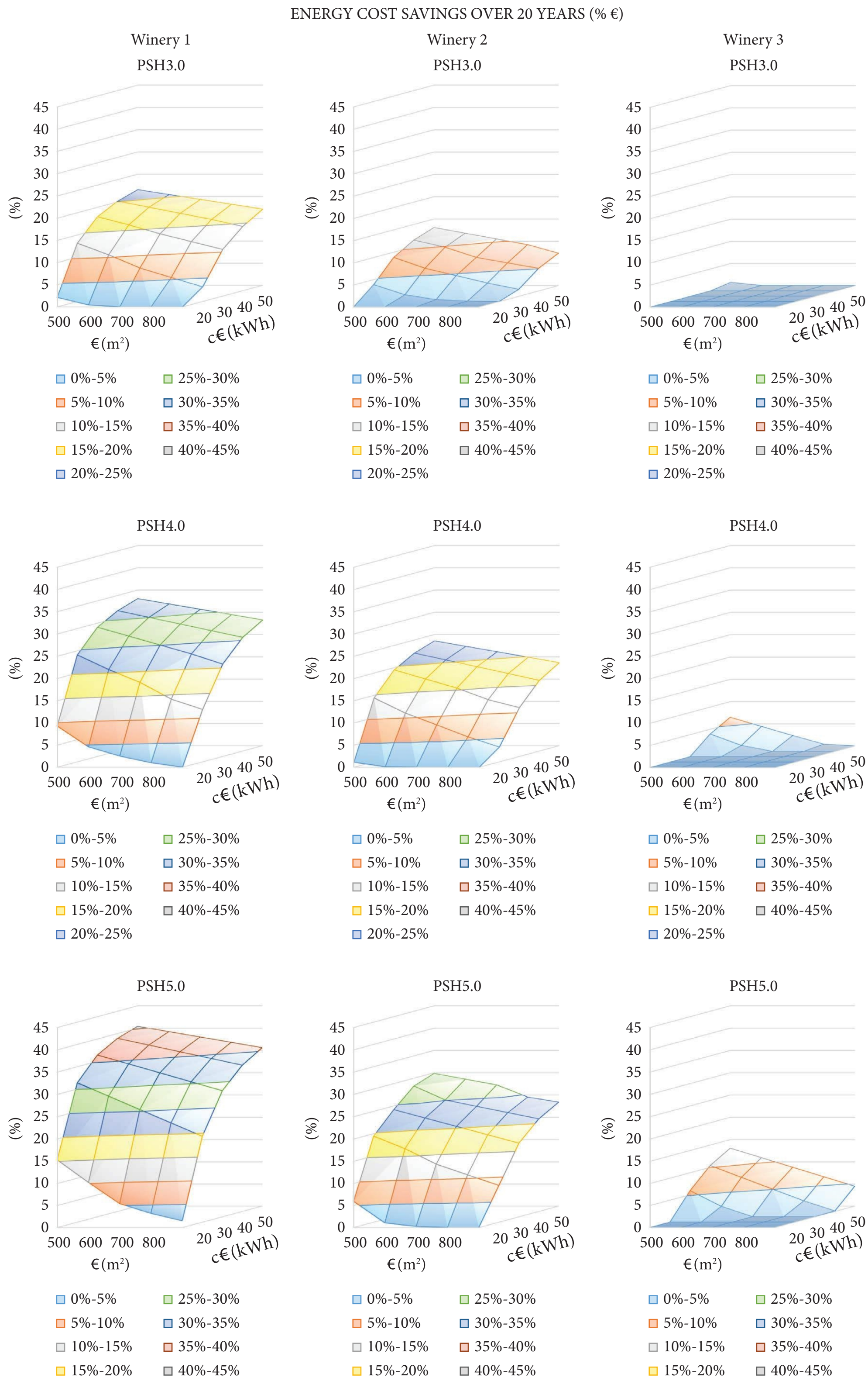


FIGURE 7: Energy cost savings (investment + annual bills for 20 years) achieved by the optimized sizing SWHS in the different scenarios analyzed.

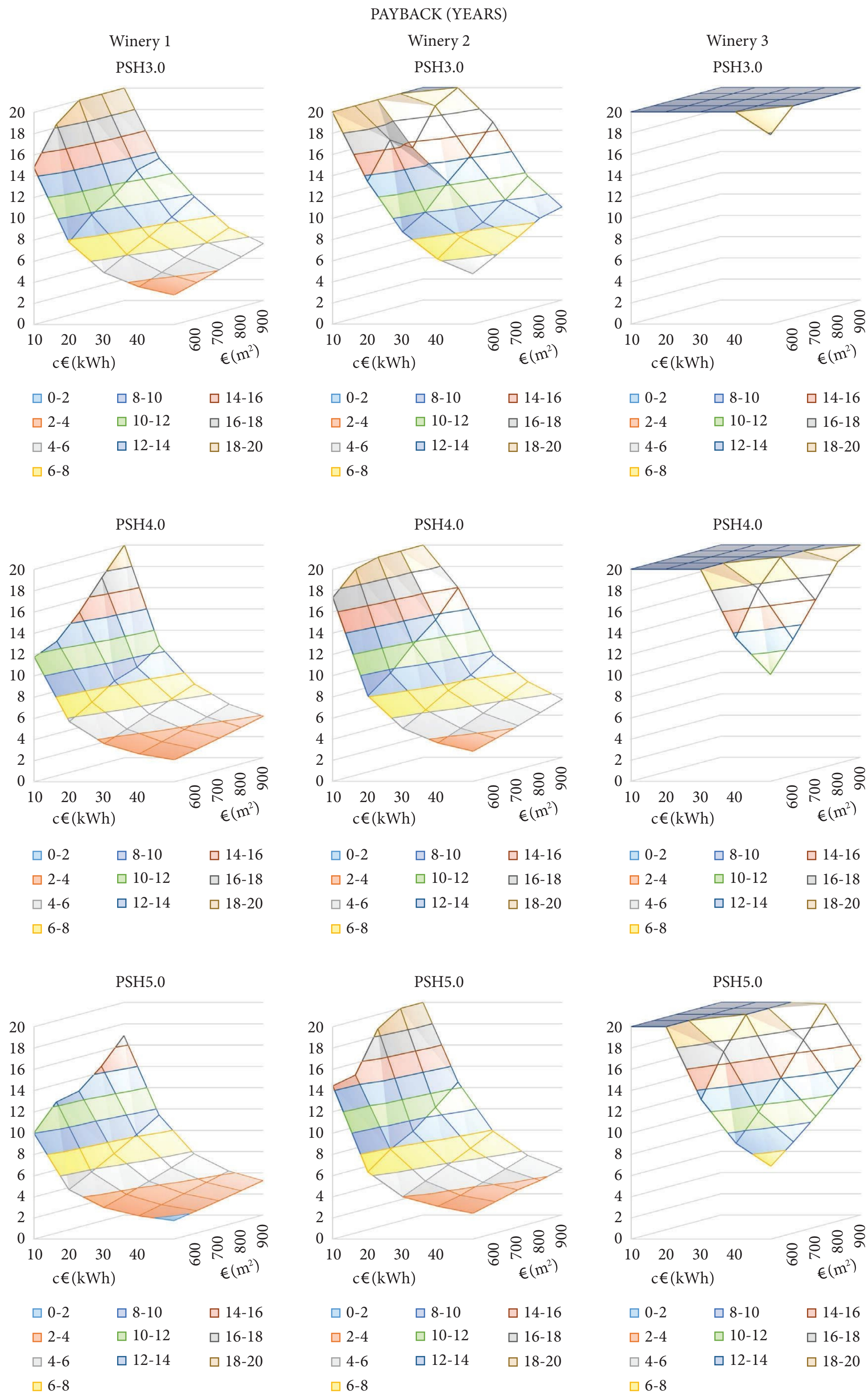


Figure 8: Payback of the optimized sizing SWHS investment in the different scenarios analyzed.

With pattern 3, in most of the scenarios analyzed, it is not possible to reduce energy consumption without incurring economic losses. In cases where it is profitable, the reduction percentages achieved are not negligible, ranging from 18% to 33%.

3.3. Energy Cost Savings. The study results demonstrate a significant reduction in the total energy cost achieved over the lifetime of the SWHS (investment required + annual energy bills for 20 years) within the new energy context, rendering the use of SWHS much more appealing within the sector. However, it presents substantial discrepancies based on the analyzed variables (Figure 7). Therefore, when implementing an SWHS in a specific winery, it is crucial to quantify the potential savings while considering the particularities of demand, irradiation, and investment costs.

In the case of pattern 1, the SWHS generates energy cost savings in almost all the scenarios analyzed. However, the percentage of savings achieved varies greatly depending on the other parameters (Figure 7). The average value of savings achieved is 20 ± 12%, with a maximum of 40% (PSH 5.0, 500 €/m^2 and 0.5 €/kWh). Despite the appealing figures, the savings potential of the sector is lower than that of other industries with more uniform consumption, where maximum percentages of 60% can be reached [15]. In the scenarios with intermediate values close to 2023 prices (700 €/m^2 and 0.30 €/kWh), the savings range between 14% and 32% depending on the location.

By analyzing pattern 2, it is observed that the greater number of days without hot water demand in this winery limits the savings achieved. The average value is reduced to 12 ± 9%, with a maximum of 30%. Notwithstanding the demand's irregularity, these values exceed those obtained in industries with more uniform patterns prior to the energy context shift (maximum of 25%) [10]. The current context enhances the viability and profitability of SWHS within the sector. In the scenarios of intermediate values close to 2023 prices, the savings range between 5% and 20% depending on the location (Figure 7).

Demand pattern 3, characterized by a few days of hot water consumption and a small volume, leads to little or no potential savings. The average for the set of cases is only 1 ± 3%. Even in the most favorable cases, the savings generated are very limited, with an absolute maximum value of 13%.

3.4. Profitability. The increase in energy prices over recent years has led to a significant rise in the profitability of SWHS, making their investment much more attractive. Even in scenarios where it was previously not profitable, it becomes an interesting alternative to conventional energy sources. Except in scenarios with highly irregular hot water consumption (pattern 3), the increase from 0.10 €/kWh to 0.20 €/kWh results in reductions in payback by several years, halving in many cases (Figure 8).

The demand pattern is a key factor in the profitability of SWHS. When the demand is relatively constant and uniform, the investment is profitable in most cases, reaching very low paybacks in the most favorable scenarios. On the contrary, when consumption is punctual and concentrated in a few days, SWHS profitability is limited, with high paybacks even in the most favorable scenarios. Nevertheless, the rest of the involved variables also cause significant differences in profitability, requiring a detailed analysis of the wide range of scenarios present. In order to contribute to the promotion of SWHS in wineries, a comprehensive analysis of the diverse range of scenarios is essential, offering a global perspective to aid in decision-making processes.

By analyzing the most favorable pattern (large winery), it is seen that the SWHS is profitable in almost all the scenarios analyzed, except in 4 very unfavorable cases where low energy cost, high SWHS price, and insufficient radiation are combined (Figure 8). However, to achieve attractive paybacks, it is necessary to have favorable values of these parameters, with a high energy price (€/kWh), a low investment cost (€/m^2), a location with high radiation, and/or combinations of more moderate values of these parameters.

The average payback value for the scenarios analyzed that are profitable is 6.8 ± 4.4 years, with a minimum of 1.7 for PSH 5.0, 500 €/m2 investment required, and an energy price of 0.5 €/kWh. In the scenarios of intermediate values (2023 energy prices of many countries), with 700 €/m^2 and 0.30 €/kWh (assuming electric water heaters), the payback ranges between 4.3 and 7.2 years depending on the location. In the current energy context, the paybacks are even lower than the values obtained in previous studies conducted before energy price hikes in highly favorable scenarios for industries with more uniform demand patterns, such as meat processing industries [10]. This highlights the substantial impetus that the new energy context offers for the deployment of SWHS.

With pattern 2, the higher number of days without demand leads to a loss of profitability of the required investment. To achieve attractive paybacks, it is necessary to combine a minimum energy price of 0.30 €/kWh with values below 700 €/m^2 and/or high radiation (Figure 8). Thus, the average payback value for the analyzed scenarios that are profitable increases to 8.6 ± 5.4 years. To make the investment more attractive, it is essential to achieve lower investment costs. Thus, the payback for the most extreme scenario is still very low, only 2.4 years. Considering intermediate scenarios (700 €/m^2 and 0.30 €/kWh), the payback ranges from 5.9 to 12.3 years depending on the location.

For pattern 3, irregular and occasional demands hinder the viability of the SWHS, which is only profitable in a small number of scenarios, with unattractive values except in the most favorable case (PSH 5.0, 0.5 €/kWh, and 500 €/m^2). The average payback value excluding unprofitable scenarios is 13.8 ± 6.3 years, with an absolute minimum of 6.9 years.

4. Conclusions

Thermal solar systems have experienced significant growth in the past decade. However, their implementation in wineries has been limited due to factors such as low energy prices, irregular and seasonal demands, or the lack of data on the performance of these systems at temperatures higher than those for domestic hot water. This work demonstrates that the new energy context is shifting established paradigms, making SWHS financially attractive in a wide range of scenarios.

The hot water demand pattern is the most influential parameter in the optimized sizing and profitability of SWHS. Knowing the demand pattern of a particular winery is key to determining the feasibility of SWHS. The higher and more uniform the hot water demand, the larger the collector area required, all other parameters being equal. In addition, the new energy context promotes the design of SWHS, making it less sensitive to changes in other variables.

A relatively constant and uniform demand (pattern 1 analyzed, based on a winery with a huge production and a hot water requirement on 73% of the days in a year), is associated with a good SWHS efficiency and profitability. With the optimized collector design, mean system efficiencies close to 35% can be achieved. In analyzed scenarios with intermediate values, close to 2023 prices in many countries (700 €/m^2 and 0.30 €/kWh), the payback ranges between 4.3 and 7.2 years depending on the location. In the opposite case, when consumption is irregular and concentrated in a few days (pattern 3, based on a small family winery with low production and a hot water requirement on 19% of the days in a year), the profitability of SWHS is limited, with unattractive paybacks even in the most favorable scenarios. The maximum system efficiency does not exceed 12%.

The vast majority of wineries are somewhere in between the two extremes described. The higher the number of days without demand, the lower the efficiency and profitability of the system. For example, in the intermediate winery analyzed (pattern 2, with a hot water requirement on 58% of the days in a year), paybacks of less than 4 years can be achieved if conditions are very favorable. To achieve attractive paybacks (less than 6 years), it is necessary to combine a minimum energy price of 0.30 €/kWh with an inversion below 700 €/m^2 and high irradiation (close to 5.0 PSH, such as extensive areas in California or Southern Spain). In locations with irradiation close to 4.0 PSH (such as central Italy or the southeast of France), the required investment must fall below 600 €/m^2 to maintain this profitability. If the irradiation is low (3.0 PSH, such as southern Germany or Austria), the energy price must also be increased to 0.40 €/kWh.

The new energy context led to a significant increase in the percentage of savings achievable with SWHS. The savings are closely linked to the uniformity of demand. Considering the pattern of high profitability (pattern 1), the optimized solar system can achieve energy consumption reductions between 32% (PSH 3.0) and 52% (PSH 5.0) in more than half of the scenarios analyzed, starting at 0.20 €/kWh, which would include the current context. This percentage of energy reduction is not far from what can be achieved in an intermediate winery: 25% (PSH 3.0) to 42% (PSH 5.0). On the contrary, considering the extremely irregular pattern analyzed, corresponding to a small winery, in most scenarios, it is not possible to reduce energy consumption without incurring economic losses.

The study results demonstrate a significant reduction in the total energy cost achieved (over the lifetime of the SWHS versus the no SWHS scenario) within the new energy context. However, it is necessary to carry out a precise calculation taking into account the involved variables, as the existing savings differences are significant. Thus, the energy savings achieved annually, coupled with the initial investment required, result in a reduction in total energy cost that can reach 40% in the most favorable scenarios of pattern 1 (winery with relatively homogeneous high demand). As the uniformity and volume of water demand decrease, savings are reduced. Considering an intermediate demand pattern (2), the maximum value is 30%. When the pattern is unfavorable (pattern 3), potential savings are reduced or null, with an average of 1% and an absolute maximum of 13%.

The results of this work should serve as a useful tool for wineries' decision-making, promoting the implementation of renewable energies to achieve a more competitive and energy-efficient sector.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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