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Influence of hot water consumption patterns on the viability of low-temperature solar thermal systems in the food industry

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ABSTRACT

The thermal demand in agri-food industries is characterised by its considerable variability, hindering the implementation of Solar Water Heating Systems (SWHS). The main objective of the study is to provide an overview of how consumption patterns influence the profitability and energy savings of SWHS in the sector, while also identifying additional key variables that affect their viability. For this purpose, approximately 1,300,000 cases have been examined, considering a wide range of consumption patterns, economic variables, and locations. Demand seasonality, weekly frequency and energy prices exhibit the greatest impact on the feasibility of SWHS. Uniformity of daily demand, location and investment cost are also determinants. Thus, single-day-per-week consumption patterns make SWHS unviable in most scenarios. However, with only three non-consecutive days, feasibility increases significantly, achieving paybacks of less than 5 years and energy savings of over 40 % when conditions are highly favorable. In strongly seasonal industries, the viability of SWHS is seriously compromised. The payback in patterns with a peak consumption in the early morning can double the value with uniform one (e.g., from 4 to 8 years in the most favorable scenarios at a price of 0.1 €/kWh). The results tables reflecting payback and energy savings in thousands of different scenarios represent a valuable tool for decision-making in industries. By looking for the scenario with the most similar characteristics, it is possible to estimate the profitability and savings of the SWHS in a given industry, as well as the possible variations when changing the assumed variables.

1. Introduction

This comprehensive study evaluates the feasibility of Solar Water Heating Systems (SWHS) in the food industry. The main objective of the study is to provide an overview of how consumption patterns influence the profitability and energy savings of SWHS in the sector, while also identifying additional key variables that affect their viability.

The use of SWHS for water heating has experienced a significant growth, with installed capacity worldwide having doubled in the last decade [1]. Among the most common collectors, there is a notable increase in the adoption of Evacuated Tube Collectors (ETC) compared to Flat Plate Collectors (FPC), owing to advantages such as superior performance, especially in cold climates. The performance of an ETC system is 41 % better than that of an FPC system, and the yearly useful energy gain of ETC is 30 % higher than that of FPC in cold climates [2]. In 2021, a considerable portion of the new installed capacity globally was attributed to ETC systems, primarily due to their prevalence in leading countries such as China and India [1]. It is expected that ongoing advancements, including the use of reflectors, nanofluids, and phase change materials [3], will continue to drive their widespread adoption in the coming years.

The industrial sector is increasingly recognizing the value of solar energy since it can cut energy charges while simultaneously promoting energy security and environmental sustainability [4]. This growing interest is reflected in the scientific community, with several review

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Abbreviations

DIN	Deutsches Institut für Normung
ETC	Evacuated Tube Collector
NPV	Net Present Value
PLC	Programmable Logic Controller
PSH	Peak Sun Hours
PTC	Positive Temperature Coefficient
SCOoPE	Saving COOPerative Energy
SWHS	Solar Water Heating System
TESLA	Transferring Energy Save Laid on Agroindustry
VBA	Visual Basic for Application

NOMENCLATURE

Ann3alt	demand on alternate days (Mondays, Wednesdays, and Fridays)
Ann3tog	demand for three consecutive days, from Monday to Wednesday
Annual1	demand one day per week
Annual5	demand for five consecutive days, from Monday to Friday
Annual7	demand every day of the week
AuWin5	demand in autumn and winter, from Monday to Friday
Aut5	exclusive demand in autumn, from Monday to Friday
c_p:	specific heat
G	irradiance
η_{0s}	zero loss efficiency
Q_{SWH}	useful energy that the experimental SWHS can store within the tank
SpSu5	demand in spring and summer, from Monday to Friday
SpSuAu5	demand all year except winter, from Monday to Friday
Spr5	exclusive demand in spring, from Monday to Friday
T_a	ambient temperature
T_t	water temperature within the tank
V_t	volume of the tank
Win5	exclusive demand in winter, from Monday to Friday
ΔE	energy change
a_{1S}	first heat loss coefficient
a_{2S}	second-order heat loss coefficient
ρ	fluid density

articles published in recent years focusing on advances in the industrial sector [5–8]. The efficiency of SWHS-ETC in industrial processes can exceed 45 % [9].

Amid the industrial sectors, the agri-food industry emerges as a pivotal focus for this study, driven by its economical importance, significant energy consumption and crucial role in the transition from fossil fuels to renewable sources. The EU food and drink industry employs 4.6 million people, generates a turnover of €1.1 trillion and €229 billion in value added, making it one of the largest manufacturing industries [10]. It stands out as one of the largest energy consumers. In the EU, it ranks fourth, accounting for 12 % of the total final energy consumption (1168 PJ), according to Eurostat data. A significant portion of this consumption is attributed to water heating for cooking, disinfection, cleaning, etc.

Another peculiarity of the sector that has prompted being the subject of the present study is that the thermal demand is characterised by its considerable variability, both in temperature and frequency. Low temperatures (below 80 °C) are primarily employed for blanching, scalding, smoking, tempering, washing, and cleaning, while medium temperatures (80–250 °C) are utilized for pasteurising, sterilising, hydrolysing, and drying [11]. For instance, in a meat processing industry [12], water at temperatures ranging from 45 °C to 100 °C is required, depending on the product and operation. Some operations occur on weekdays, while others are only carried out once a week. Certain operations necessitate water for extended hours compared to those concentrated in the early morning or late afternoon, and so forth. The performance and sizing of SWHS vary depending on the required temperature [13,14], complicating feasibility studies in the sector.

The size of industries also influences the frequency of many processes, consequently affecting the regularity of hot water demand. For instance, in the winemaking sector, a very large winery may require hot water for 268 days per year, while a small one only needs it for 70 days [15].

Another differentiating feature of the agri-food industry is that many of its sectors exhibit strong seasonality, a result of harvesting or collection. For example, olives are processed during the winter months, grapes in late summer and early autumn, and so forth. This seasonality is reflected in the energy bills of these agro-industries [16].

These peculiarities of the sector, combined with other factors such as the low energy prices of a few years ago, have limited the widespread adoption of SWHS. Its implementation may face various additional challenges and barriers, encompassing regulatory, technical, and market aspects. Among others, regulatory frameworks might lack clarity and procedures can be lengthy and complex; existing infrastructures may not easily accommodate SWHS; competition with solar photovoltaic due to limited space; retrofitting existing heating systems with SWHS may require significant modifications and pose technical integration challenges; ensuring the reliability and efficiency of the SWHS require regular maintenance and training of personnel; the upfront costs can be a significant barrier, especially for smaller businesses in the food industry; limited availability of qualified suppliers and installers, etc.

Addressing these challenges requires a multi-faceted approach involving collaboration between industry stakeholders, policymakers, technology providers and researchers. Some previous studies have sought to promote SWHS by demonstrating their viability in agro-industries and specific contexts. Within the European project InSun, the design, control optimization, and performance analysis of a large-scale flat solar plate at a meat factory in Austria were analyzed. The results indicate that the average efficiency of the system is around 60 %, neglecting transient phases during the summer months [17,18]. In a different meat processing industry, paybacks of 7 years were achievable in the context of several years ago [12], reducing to half with current energy prices [19]. Both studies highlighted significant variations in the viability of SWHS depending on variables such as location. In a soft drink industry in Ethiopia, paybacks close to 6 years can be achieved [20]. In a dairy factory, solar thermal heat can considerably reduce operating costs, even in the North European climate, with paybacks of 5.5 years with optimized sizing [21]. In the winemaking sector, the seasonality and irregularity of a winery's demand pattern significantly affect the viability and profitability of SWHS. Paybacks between 4.3 and 7.2 years can be obtained in large wineries with a favorable context, while SWHS are not viable for small wineries due to demand frequency [15].

Previous studies have demonstrated the viability of SWHS in specific industries within the sector and specific context. However, as they focus on individual cases, their results are not readily extrapolatable to the vast range of existing scenarios. The profitability and energy savings achieved in a specific industry within a particular context may not be realistic in another industry, even within the same subsector, due to variations in demand patterns (temperature, frequency, etc.) and in the context (location, energy prices, etc.). The sector requires a large-scale study that examines a broad spectrum of demand patterns, encompassing different consumption frequencies and/or seasonality, to determine the impact of these patterns on the viability of SWHS.

Furthermore, the instability and increase in energy prices since 2021 make it necessary to conduct analyses of the feasibility of SWHS that encompass a broad spectrum of energy prices, aiming to reduce energy bills and achieve greater cost certainty in production. Recent studies showed reduced paybacks (5 years or less) can be achived assuming high energy prices as in the past few years [15,19,22].

Moreover, the climate emergency necessitates intensified efforts to replace fossil fuels with renewable sources. Given the economic significance and high-energy consumption of the agro-industrial sector, it represents a crucial link in this transition. In contrast to previous studies that focus on specific cases, large-scale analysis of potential energy savings and emissions reduction can be a useful tool to promote the use of renewable energy in the sector.

Through the analysis encompassing numerous demand patterns and diverse contexts, the present study identifies scenarios in which SWHS with evacuated tube collectors can be viable, quantifying their profitability and potential energy savings. To achieve this, various daily demand schedules, different weekly demand frequencies, and various possibilities of consumption seasonality have been analyzed. The ultimate goal is to promote the implementation of SWHS in the sector, assisting in the decision-making process within the industry. Although the study has focused on the agri-food industry, the results can be extrapolated to other industrial sectors as long as their consumption patterns are similar to those analyzed.

2. Material and methods

To achieve the set objective, the developed methodology has been based on the energy analysis of more than one million cases, specifically 1,296,000. To define these cases, a characterization of hot water consumption in different types of industries was carried out, establishing 60 patterns based on daily, monthly frequency, and the presence of seasonality. Each of these patterns was framed in a multitude of different contexts, considering various required temperatures, energy prices, required investment, and locations. To conduct the energy analysis, it was necessary to perform an experimental characterization of the SWHS at different required water temperatures and develop an energy simulation tool. In total, 6480 scenarios were defined, analyzing in each one

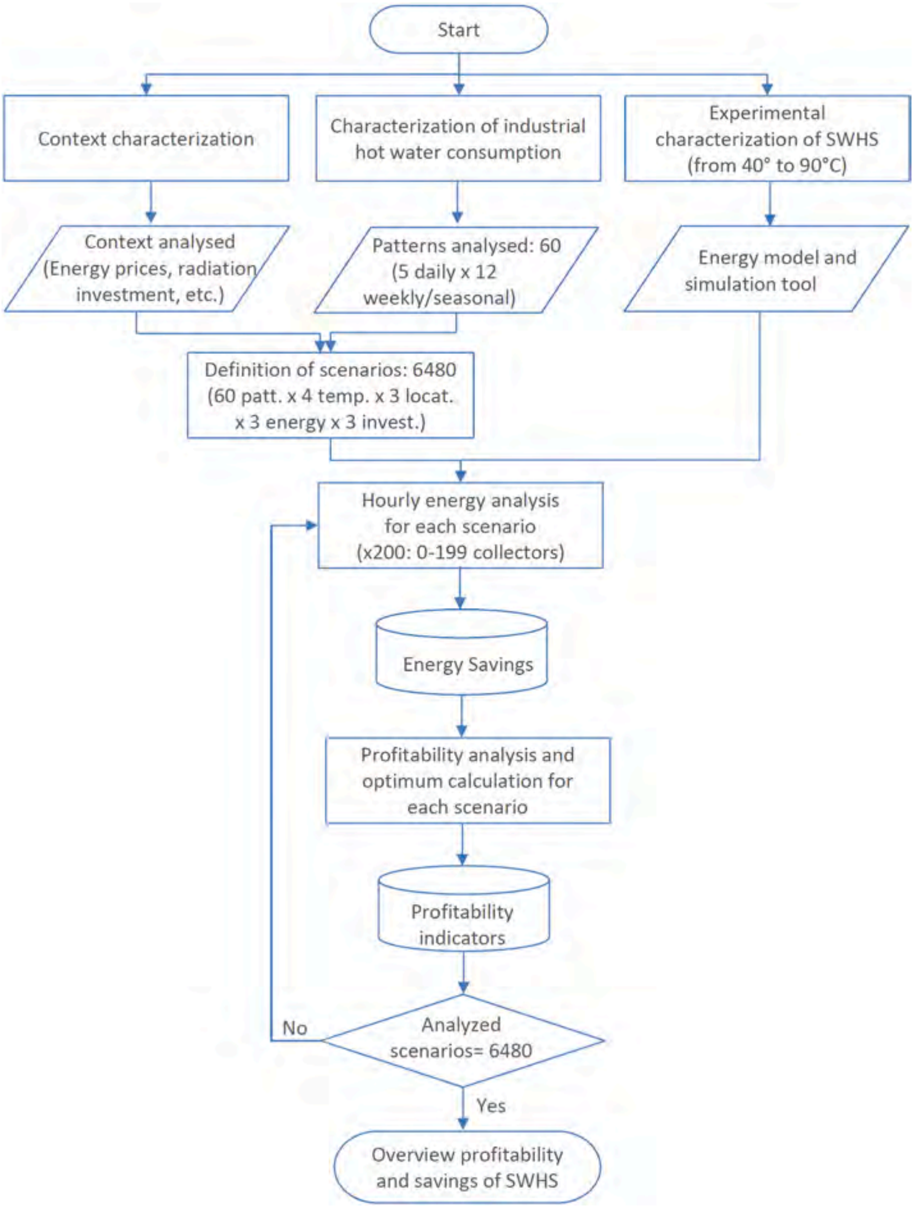


Fig. 1. Methodology flowchart.

200 different sizes to determine the optimal sizing of the SWHS in the specific context based on profitability criteria (Fig. 1).

2.1. Consumption patterns

The harvest of many foods is concentrated in a few months, causing significant peaks of activity during these periods. For example, oil mills process olives during the winter months, wineries handle grapes at the beginning of autumn, and tobacco harvesting occurs in late summer, among other instances. Furthermore, other factors such as the size of the industries or the products processed can also lead to significant differences in activities and working hours, even within the same subsector. Consequently, the food industry exhibits a highly variable pattern of hot water usage depending on the subsector and/or the activity and process involved: seasonality, days per week, distribution of demand throughout the hours of the day, temperature, etc.

Thus, for instance, in a single meat processing industry [12], water at 80 °C is required for plant cleaning, including approximately 1 h at the end of the day from Monday to Friday, a thorough cleaning on Fridays, cleaning of boards and other items for 2 h in the afternoon every day, and cleaning after sausage production for approximately 45 min. Four times a week, sausages are prepared for 2 h at 97 °C, reaching cooking at 100 °C for 30–40 min. Washing of sausage casings occurs four days per week, taking 1 or 2 h per day with water at 45 °C. Chorizo cleaning is done once a week at 80 °C for 2 h.

In the case of wineries, the seasonality and frequency of demand show enormous variations depending on the size and the processes carried out [15]. In a large winery, hot water is required for 268 days per year (most weekends throughout the year, hot water is not demanded); in a small one, hot water is only required for 70 days a year. Water at 40 °C is needed for starter preparation, 80-90 °C for bottling, 65-70 °C for filter cleaning, and 85-90 °C for barrel cleaning. At times, the demand is constant and uninterrupted throughout the day, while at other times, it is concentrated at the beginning, middle, and/or end of the day.

To provide a comprehensive overview applicable to the preliminary decision-making of almost any industry, 60 consumption patterns have been designed. These patterns combine various daily demand schedules, different weekly demand frequencies, and various possibilities of consumption seasonality. These simplified patterns have been designed based on the extensive prior experience of the research team in characterizing the energy consumption of agro-industries, highlighting their involvement in European projects such as TESLA (Transferring Energy Save Laid on Agroindustry) and SCOoPE (Saving COOPerative Energy).

To compare the patterns under the same frame of reference, a consistent daily volume of 7 m^3 has been considered, which will be evenly distributed based on the hours of the day when there is demand. The selected daily volume closely approximates that recorded during peak demand days in the previously described meat industry [12]. While the daily demand remains constant, the annual consumption will increase proportionally with the extended frequency of demand days in the selected pattern. This observation mirrors scenarios observed in various industries, such as those operating exclusively on weekdays as opposed to seven days a week, or distinguishing between cleaning processes conducted solely during harvest periods as opposed to daily cleaning routines. While the assumed volume will influence the size of the installation, it will not have an impact on the energy savings achieved, expressed as a percentage of the total, nor the payback of the optimized installation based on the criteria that will be defined later on. Specifically, the analyzed variations include:

- 5 daily demand schedules (Fig. 2a): “Uniform” from 7:00 to 21:00 (0.5 m^3 per hour), “Initial” from 7:00 to 9:00 (3.5 m^3/h), “Final” from 19:00 to 21:00 (3.5 m^3/h), “Middle” from 13:00 to 15:00 (3.5 m^3/h), and “Double” as a combination of Initial and Final (1.75 m^3/h).
- 5 weekly demand variants (Fig. 2b): One day (Annual1), Mondays, Wednesdays, and Fridays (Ann3alt), Three consecutive days, Monday to Wednesday (Ann3tog), Five consecutive days, Monday to Friday, (Annual5), and Every day of the week (Annual7).
- 7 seasonality scenarios with demand from Monday to Friday: Exclusive demand in spring (Spr5), in summer (Sum5), in autumn (Aut5), in winter (Win5), in spring and summer (SpSu5), in autumn and winter (AuWin5), and all year except winter (SpSuAu5).

The 60 analyzed patterns result from combining each of the daily demand patterns with the five weekly demand variants and the seven seasonality scenarios.

2.2. Context and definition of scenarios

In order for the study to serve as a comprehensive reference for industries on a global scale, it has been necessary to define a broad spectrum of scenarios. A wide range of water temperatures was considered, grounded in the vast industrial casuistry, encompassing diverse energy prices reflective of recent fluctuations, and incorporating locations characterized by low, medium, and high radiation levels. Additionally, a comprehensive range of investment costs was factored in. Nevertheless, to simplify the visualization and discussion of the results, it was necessary to limit the immense casuistry to a limited number of representative values. Specifically, 6480 scenarios have been defined, a combination of the 60 patterns described earlier with four temperatures, three energy prices, three locations, and three investment cost values.

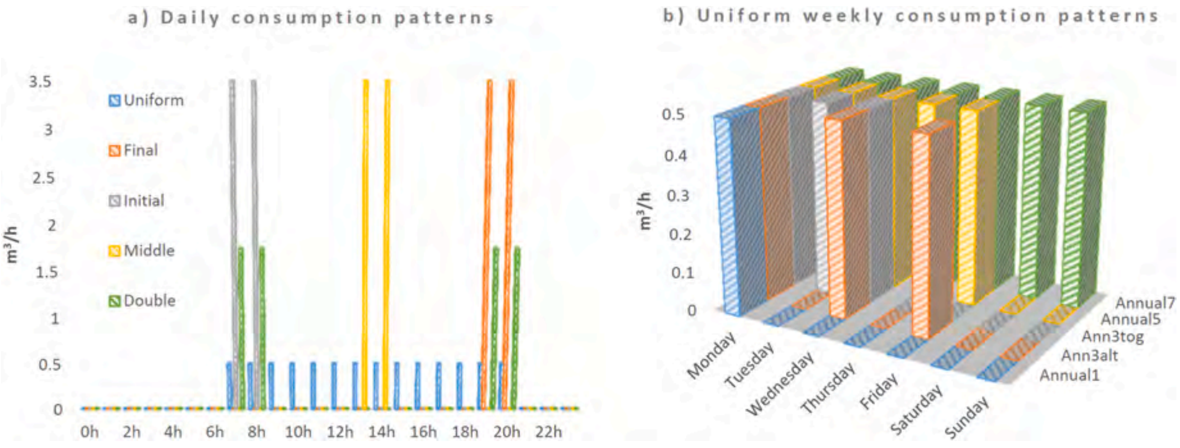


Fig. 2. Daily (a) and weekly (b) consumption pattern variations for the case of uniform demand.

2.2.1. *Required temperature*

Considering the extensive casuistry of demanded temperatures outlined previously, the study has been conducted by categorizing four water temperatures with an interval of 15 °C between them. Specifically, 40 °C, 55 °C, 70 °C, and 85 °C.

2.2.2. *Energy prices*

In recent years, energy prices have undergone significant fluctuations. For instance, in Spain, the average price of electrical kWh offered to industries surged from values close to 10c€ in March 2021 to 30c€ a year later, reaching approximately 50c€ when factoring in power demand costs, taxes, and other charges [16]. Similar trends have been observed for fossil fuels such as gas and diesel.

To simplify the visualization of results, three energy price values (including taxes) have been considered, without differentiation based on the supply type. Specifically, 0.10€/kWh, a value close to energy prices from a few years ago; 0.30 €/kWh, a value close to the current electricity price in countries like Spain; 0.50 €/kWh, the maximum value reached during the energy crisis following the Ukraine War.

2.2.3. *Irradiance and temperature in the analyzed locations*

To ensure that the obtained results serve as a broad-scale reference, three locations with markedly different radiation and ambient temperature have been selected, quantified in terms of Peak Sun Hours (PSH) on the horizontal plane. Irradiance data, external ambient temperature, and ground temperature at 0.5 m (utilized to estimate the temperature of water from the underground supply network) have been extracted from the climatological files of EnergyPlus (*epw), specifically:

- DEU_Stuttgart.107380_IWEC: PSH 3.0
- ITA_Rome.162420_IWEC: PSH 4.0
- USA_CA_Los.Angeles.Intl.AP.722950_TMY: PSH 5.0

Through a straightforward annual simulation of a surface with an inclination equal to the latitude of the location and south-facing orientation, the EnergyPlus program provides hourly values of irradiance on the inclined plane (the solar collector's plane) and external temperature.

The calculations were conducted assuming that the water storage tank is located inside the industrial facility to minimize system efficiency losses. Consequently, it is essential to narrow down the vast array of possible industrial facilities to estimate a typical and realistic interior temperature. To achieve this, a simulation model developed and previously validated was employed. This model enables the calculation of the interior temperature of a non-climatized agro-industrial facility dedicated to wine storage and aging [23]. Following simulations with climatological files for each location, the EnergyPlus program provided hourly values of the interior temperature inside the facility for all 365 days of the year.

2.2.4. *Investment*

A wide spectrum of factors contributes to the investment needed for the implementation of a SWHS. These include the type and size of collectors, manufacturer of system components, local labour expenses, roof inclination, subsidies, etc. Therefore, the study covers a wide range of investment costs including installation and administrative procedures, selecting three cases for the best visualization of the results: 500 €/m^2, 700 €/m^2 and 900 €/m^2.

2.2.5. *Solar installation size*

Within each scenario, 200 different installation sizes have been analyzed, ranging from one to 200 solar collectors, each with a surface area of 2 m^2. The objective is to determine the optimal sizing based on profitability criteria that will be explained later on. In total, an energy analysis will be conducted for 1,296,000 distinct cases.

2.3. *Energy captured by the SWHS*

To characterise the performance of an SWHS with active circulation across the wide range of temperatures demanded in industries, distinct from those typically encountered in domestic use, it was essential to devise and monitorized an experimental system. The SWHS was designed utilizing vacuum tube collectors as they exhibit superior performance compared to Flat Plate Collectors (FPC) in colder climates [2] and facilitate attaining higher temperatures [13,24]. This typology has experienced greater implementation in recent years.

The experimental SWHS used in this work replicates existing systems available in the market. Nevertheless, it has monitoring and control subsystems that enable temperature variations from 40 °C to 90 °C while monitoring key variables crucial for quantifying captured useful energy. Over a year-long period, the system's behaviour was continuously monitored at 1-min intervals, in cycles that varied the required temperature on a daily basis.

The chosen vacuum-tube solar collector, a WesTech Solar Co. model SP-S58/1800–24, incorporates 24 vacuum tubes encompassing a net collection area of 2 m^2. Positioned at a 41° angle facing due south, this configuration ensures optimal annual performance. The accumulator, a Thermor IAV 80/100 model, incorporates an exchange system through a coil and affords an 80 L capacity. Featuring high-density thermal insulation and a glazed stainless-steel container, it assures efficient and effective energy storage. The hydraulic circuit comprises copper pipes measuring 20 mm in inner diameter and 1 mm in thickness, encased in 13 mm-thick insulation. The fluid flow is regulated by the Wilo-Star-ST 15/6 ECO-3 submerged rotor pump with 42W power. Controlled by two regulatory subunits, namely, an Allegro 453 controller from Sonder responsible for managing the collector circuit pump and an automatic PLC Logo from Siemens overseeing tank discharge, the system utilizes PTC 1000 type control probes. Meteorological data were recorded utilizing the Micro Weather Station HOBO manufactured by Onset. The installed pyranometer was aligned at an identical angle to the vacuum tubes.

The described experimental system has been utilized in prior studies for energy characterization at different temperatures [13,24,25], and more recently, in investigations focused on a meat industry [19] and three wineries [15]. Following a consistent methodology, the energy simulation hinges on a model designed to estimate the useful energy that the experimental SWHS can store within the tank (Q_{SWH}, W m^{-2}). This model derives this energy calculation from irradiance (G, W m^{-2}), ambient temperature (T_a, °C), and the water temperature within the tank (T_t, °C), as described by Equation (1).

$$\begin{aligned} Q_{SWH} &= \eta_{0S} G - a_{1S}(T_t - T_a) - a_{2S}(T_t - T_a)^2 \\ &= 0,7551G - 43,2053(T_t - T_a) - 0,2905(T_t - T_a)^2 \end{aligned} \tag{1}$$

Here, η_{0s} represents the zero loss efficiency, a_{1S} denotes the first heat loss coefficient (W m^{-2} °C^{-1}) and a_{2S} the second order heat loss coefficient (W m^{-2} °C^{-2}). These constants were calculated using a year-long dataset obtained through monitoring, minimizing the disparity between the energy computed by the model and the factual energy transferred into the tank ($R^2 = 0.994$, typical error 279 Wh m^{-2} d^{-1}).

2.4. *Energy analysis*

To carry out the energy analysis in each of the proposed cases (almost 1,300,000), a simulation tool developed with Visual Basic for Application (VBA) has been utilized. This tool is the same as the one used in the two recently published works cited earlier [15,19]. It performs an energy balance for each hour of the year, determining the water temperature in the tank through gains from the collector. To achieve this, it multiplies the energy obtained using equation (1) by the collector's area specific to each case. Additionally, it calculates the exchange of energy with the air surrounding the tank, as well as the energy extracted in the demanded water. Consequently, the water temperature within the tank (T_t) experiences hourly fluctuations in accordance with energy changes (ΔE, Wh), taking into account the tank's volume (V_t, m^3), fluid density (ρ, kg m^{-3}), and specific heat (c_p, Wh kg^{-1} °C^{-1}). Thus, the temperature at any hourly interval ($T_{t,after}$) has been calculated based on the temperature in the preceding hourly interval ($T_{t,before}$), taking into account temperature variations according to Equation (2):

$$T_{t,after} = T_{t,before} + \frac{\Delta E}{V_t \cdot \rho \cdot c_p} \tag{2}$$

Employing a consistent reference frame across all scenarios, tank losses were estimated at 1.2 kW/24h in accordance with DIN 4753/8 standards (at 65 °C internal tank temperature and 20 °C external temperature). Losses were computed by multiplying the temperature differential (between tank water and ambient temperature) by the thermal transmittance of the tank insulation and the tank's surface area.

The energy reduction resulting from water extracted from the tank is calculated based on the demanded energy, obtained by multiplying the necessary volume by the temperature variance between the required water temperature and the supply network's water temperature. If the demanded temperature exceeded the tank temperature, the corresponding volume was withdrawn (up to the tank's limit), with any remaining energy required to attain the desired temperature provided by the conventional supply system. Conversely, if the demanded temperature fell below the tank temperature, the withdrawn volume was adjusted by mixing with cold water. The energy provided by the conventional system was determined as the disparity between the demanded energy and that supplied by the SWHS.

After completing the annual energy balance, the application calculates the total energy demanded by the industry, determining what percentage of it is supplied by the SHWS and what percentage by the conventional supply system. It also calculates the total radiation incident for the subsequent calculation of the system's efficiency.

2.5. Profitability analysis

The profitability analysis has been carried out assuming a solar system lifetime of 20 years and a discount rate of 1.5 %. In order to guarantee the achievement of SWHS high productivity, systems require maintenance at least once a year [26]. Therefore, an annual maintenance cost of 2 % of the investment has been taken into account in the calculations. For each scenario, the tool begins by calculating the energy cost of the industry over 20 years without a solar system as a reference case to determine the achieved savings. This cost is calculated as the Net Present Value (NPV), taking into account annual energy bills and the discount rate. The annual bill is obtained by multiplying the total energy required for water heating (kWh) by the energy price of the scenario (€/kWh, including taxes and other items).

Subsequently, for each of the 200 cases in the scenario, it repeats the calculation of the total energy cost, in an equivalent manner to the reference case. The NPV over 20 years is calculated taking into account the annual cost, the initial investment and the discount rate. The annual cost is obtained by adding the conventional supply cost (demanded energy * €/kWh) plus the maintenance and operation cost (pump running hours * hourly consumption) of the solar system. The initial investment required has been calculated by multiplying the collector surface of the case by the reference price of the installation (€/m^2).

From these values, the annual savings generated have been calculated. Based on the investment and the annual savings, the discounted payback has been calculated (equation (3)):

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

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

While a specific calculation considering subsidies has not been conducted, the various investment values analyzed allow for an indirect evaluation of their impact by subtracting the subsidy amount from the required investment. Furthermore, to avoid further complicating the scenarios, external financing has not been considered for the investment.

2.6. Optimum determination

To determine which of the 200 cases is optimal in each scenario, two sizing criteria have been calculated and evaluated. The first criterion aims to achieve the maximum savings in energy cost over the 20-year lifespan of the installation, considering the initial investment, annual bills and maintenance cost. The second criterion is a more conservative approach, seeking to balance savings and a rapid return on investment, specifically maximizing the "savings/payback" ratio, dividing the percentage of savings achieved by the discounted payback.

Upon completion of the computation and analysis of the 6480 scenarios, it was discerned that a substantial portion of these scenarios exhibited a noteworthy augmentation in the collection area when maximizing savings. This led to a consequential escalation in the requisite investment, achieving only a marginal increment in the realised savings. This is attributed to the fact that around the inflection point of the savings curve, there is a wide range of sizes where small variations in achieved savings occur (Fig. 3). Given the energy context characterized by strong instability in recent years, the decision has been made to choose the "Maximize Savings/Payback Ratio" criterion for system design. This approach achieves comparable savings with smaller installations, thereby reducing the risk associated with future fluctuations of energy price.

3. Results and discussions

The results presented below pertain to the optimal cases, assuming the criterion of maximizing the "Savings/Payback" ratio. When employing the alternative criterion, the average value of the energy bill savings over the 20-year lifespan of the SWHS in the set of profitable scenarios is only 1 ± 1 % higher compared to the "Savings/Payback" criterion. The primary advantage of prioritizing savings maximization is that the reduction in annual energy consumption increases by an average of 5 ± 4 %, bringing about associated environmental benefits. However, a notable drawback is that the average size of the required installation increases by 15 ± 14 %, surpassing 50 % in scenarios with higher uniformity. Additionally, the payback period extends, albeit with an average across scenarios lower than 1 year.

3.1. Profitability

Fig. 4 (results for PSH 3.0), Fig. 5 (results for PSH 4.0) and Fig. 6 (results for PSH 5.0) provide a breakdown of the payback period for the

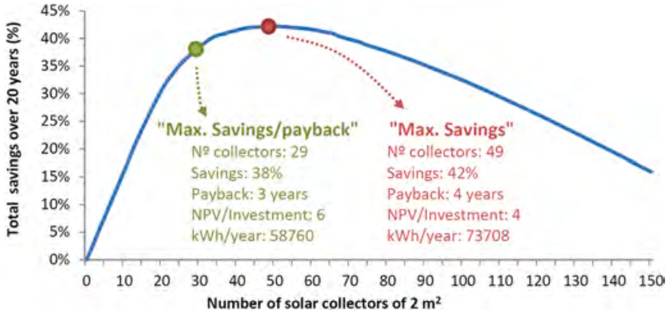
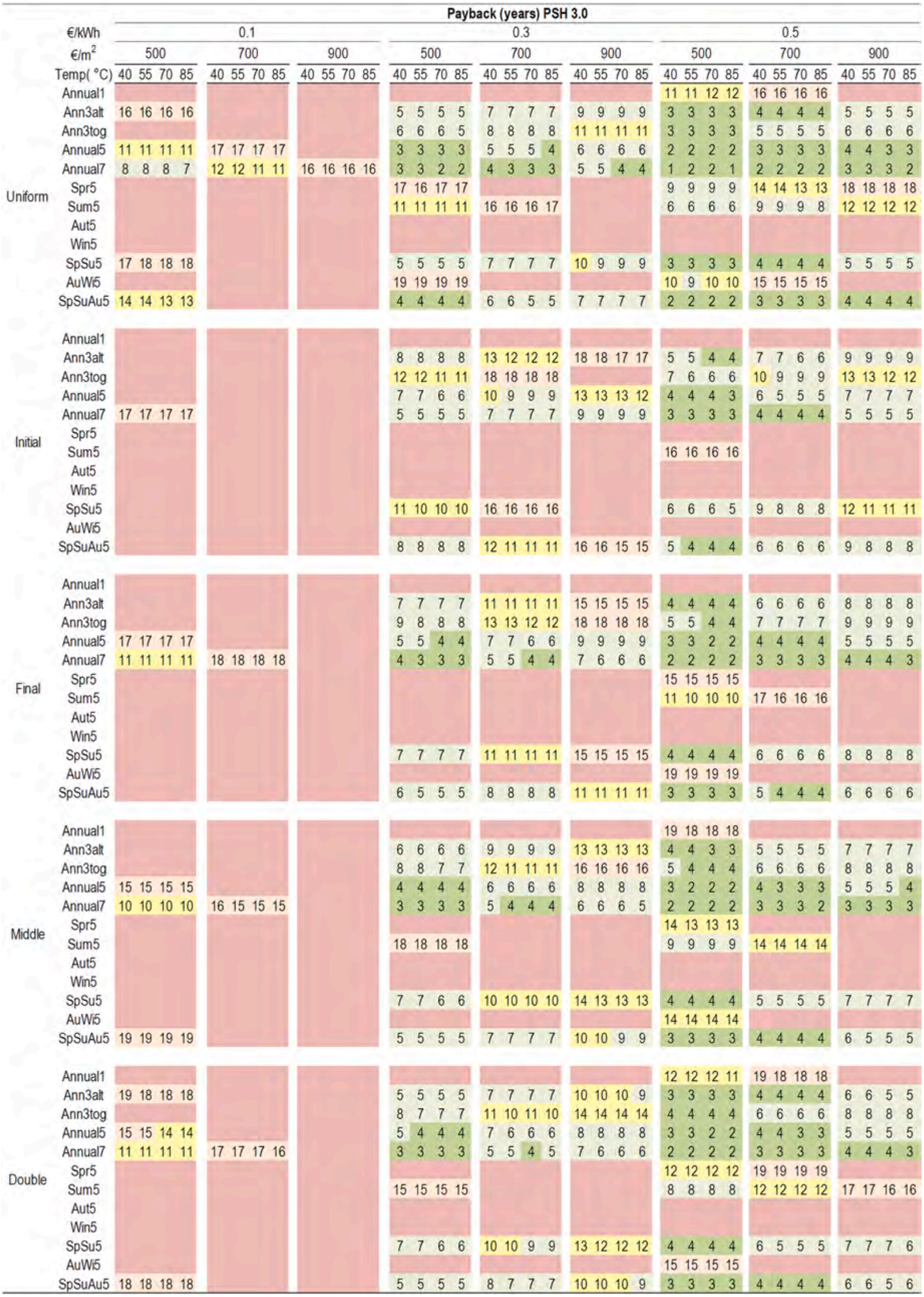


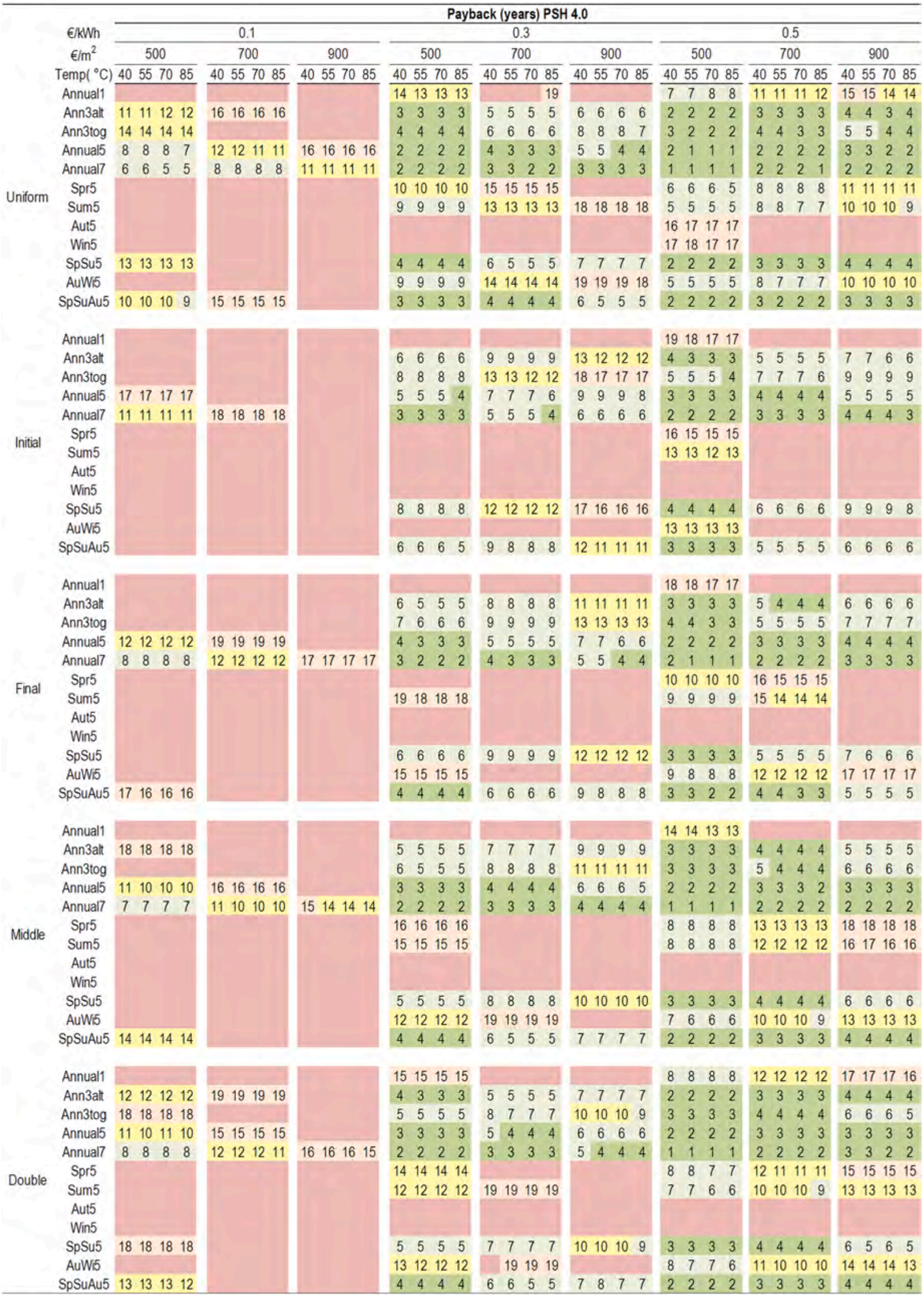
Fig. 3. Example illustrating the variation of achieved savings based on the size of the installation, identifying cases of maximum savings and maximum "Savings/Payback" Ratio.



Payback (years) PSH 3.0

	€/kWh	0.1												0.3												0.5											
	€/m^2	500				700				900				500				700				900				500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1																									11	11	12	12	16	16	16	16				
	Ann3alt	16	16	16	16									5	5	5	5	7	7	7	7	9	9	9	9	3	3	3	3	4	4	4	4	5	5	5	5
	Ann3tog													6	6	6	5	8	8	8	8	11	11	11	11	3	3	3	3	5	5	5	5	6	6	6	6
	Annual5	11	11	11	11	17	17	17	17					3	3	3	3	5	5	5	4	6	6	6	6	2	2	2	2	3	3	3	3	4	4	3	3
	Annual7	8	8	8	7	12	12	11	11	16	16	16	16	3	3	2	2	4	3	3	3	5	5	4	4	1	2	2	1	2	2	2	2	3	3	3	2
	Spr5													17	16	17	17									9	9	9	9	14	14	13	13	18	18	18	18
	Sum5													11	11	11	11	16	16	16	17					6	6	6	6	9	9	9	8	12	12	12	12
	Aut5																																				
	Win5																																				
	SpSu5	17	18	18	18									5	5	5	5	7	7	7	7	10	9	9	9	3	3	3	3	4	4	4	4	5	5	5	5
	AuWi5													19	19	19	19									10	9	10	10	15	15	15	15				
	SpSuAu5	14	14	13	13									4	4	4	4	6	6	5	5	7	7	7	7	2	2	2	2	3	3	3	3	4	4	4	4
Initial	Annual1																																				
	Ann3alt													8	8	8	8	13	12	12	12	18	18	17	17	5	5	4	4	7	7	6	6	9	9	9	9
	Ann3tog													12	12	11	11	18	18	18	18					7	6	6	6	10	9	9	9	13	13	12	12
	Annual5													7	7	6	6	10	9	9	9	13	13	13	12	4	4	4	3	6	5	5	5	7	7	7	7
	Annual7	17	17	17	17									5	5	5	5	7	7	7	7	9	9	9	9	3	3	3	3	4	4	4	4	5	5	5	5
	Spr5																																				
	Sum5																									16	16	16	16								
	Aut5																																				
	Win5																																				
	SpSu5													11	10	10	10	16	16	16	16					6	6	6	5	9	8	8	8	12	11	11	11
	AuWi5																																				
	SpSuAu5													8	8	8	8	12	11	11	11	16	16	15	15	5	4	4	4	6	6	6	6	9	8	8	8
Final	Annual1																																				
	Ann3alt													7	7	7	7	11	11	11	11	15	15	15	15	4	4	4	4	6	6	6	6	8	8	8	8
	Ann3tog													9	8	8	8	13	13	12	12	18	18	18	18	5	5	4	4	7	7	7	7	9	9	9	9
	Annual5	17	17	17	17									5	5	4	4	7	7	6	6	9	9	9	9	3	3	2	2	4	4	4	4	5	5	5	5
	Annual7	11	11	11	11	18	18	18	18					4	3	3	3	5	5	4	4	7	6	6	6	2	2	2	2	3	3	3	3	4	4	4	3
	Spr5																									15	15	15	15								
	Sum5																									11	10	10	10	17	16	16	16				
	Aut5																																				
	Win5																																				
	SpSu5													7	7	7	7	11	11	11	11	15	15	15	15	4	4	4	4	6	6	6	6	8	8	8	8
	AuWi5																									19	19	19	19								
	SpSuAu5													6	5	5	5	8	8	8	8	11	11	11	11	3	3	3	3	5	4	4	4	6	6	6	6
Middle	Annual1																									19	18	18	18								
	Ann3alt													6	6	6	6	9	9	9	9	13	13	13	13	4	4	3	3	5	5	5	5	7	7	7	7
	Ann3tog													8	8	7	7	12	11	11	11	16	16	16	16	5	4	4	4	6	6	6	6	8	8	8	8
	Annual5	15	15	15	15									4	4	4	4	6	6	6	6	8	8	8	8	3	2	2	2	4	3	3	3	5	5	5	4
	Annual7	10	10	10	10	16	15	15	15					3	3	3	3	5	4	4	4	6	6	6	5	2	2	2	2	3	3	3	2	3	3	3	3
	Spr5																									14	13	13	13								
	Sum5													18	18	18	18									9	9	9	9	14	14	14	14				
	Aut5																																				
	Win5																																				
	SpSu5													7	7	6	6	10	10	10	10	14	13	13	13	4	4	4	4	5	5	5	5	7	7	7	7
	AuWi5																									14	14	14	14								
	SpSuAu5	19	19	19	19									5	5	5	5	7	7	7	7	10	10	9	9	3	3	3	3	4	4	4	4	6	5	5	5
Double	Annual1																									12	12	12	11	19	18	18	18				
	Ann3alt	19	18	18	18									5	5	5	5	7	7	7	7	10	10	10	9	3	3	3	3	4	4	4	4	6	6	5	5
	Ann3tog													8	7	7	7	11	10	11	10	14	14	14	14	4	4	4	4	6	6	6	6	8	8	8	8
	Annual5	15	15	14	14									5	4	4	4	7	6	6	6	8	8	8	8	3	3	2	2	4	4	3	3	5	5	5	5
	Annual7	11	11	11	11	17	17	17	16					3	3	3	3	5	5	4	5	7	6	6	6	2	2	2	2	3	3	3	3	4	4	4	3
	Spr5																									12	12	12	12	19	19	19	19				
	Sum5													15	15	15	15									8	8	8	8	12	12	12	12	17	17	16	16
	Aut5																																				
	Win5																																				
	SpSu5													7	7	6	6	10	10	9	9	13	12	12	12	4	4	4	4	6	5	5	5	7	7	7	6
	AuWi5																									15	15	15	15								
	SpSuAu5	18	18	18	18									5	5	5	5	8	7	7	7	10	10	10	9	3	3	3	3	4	4	4	4	6	6	5	6

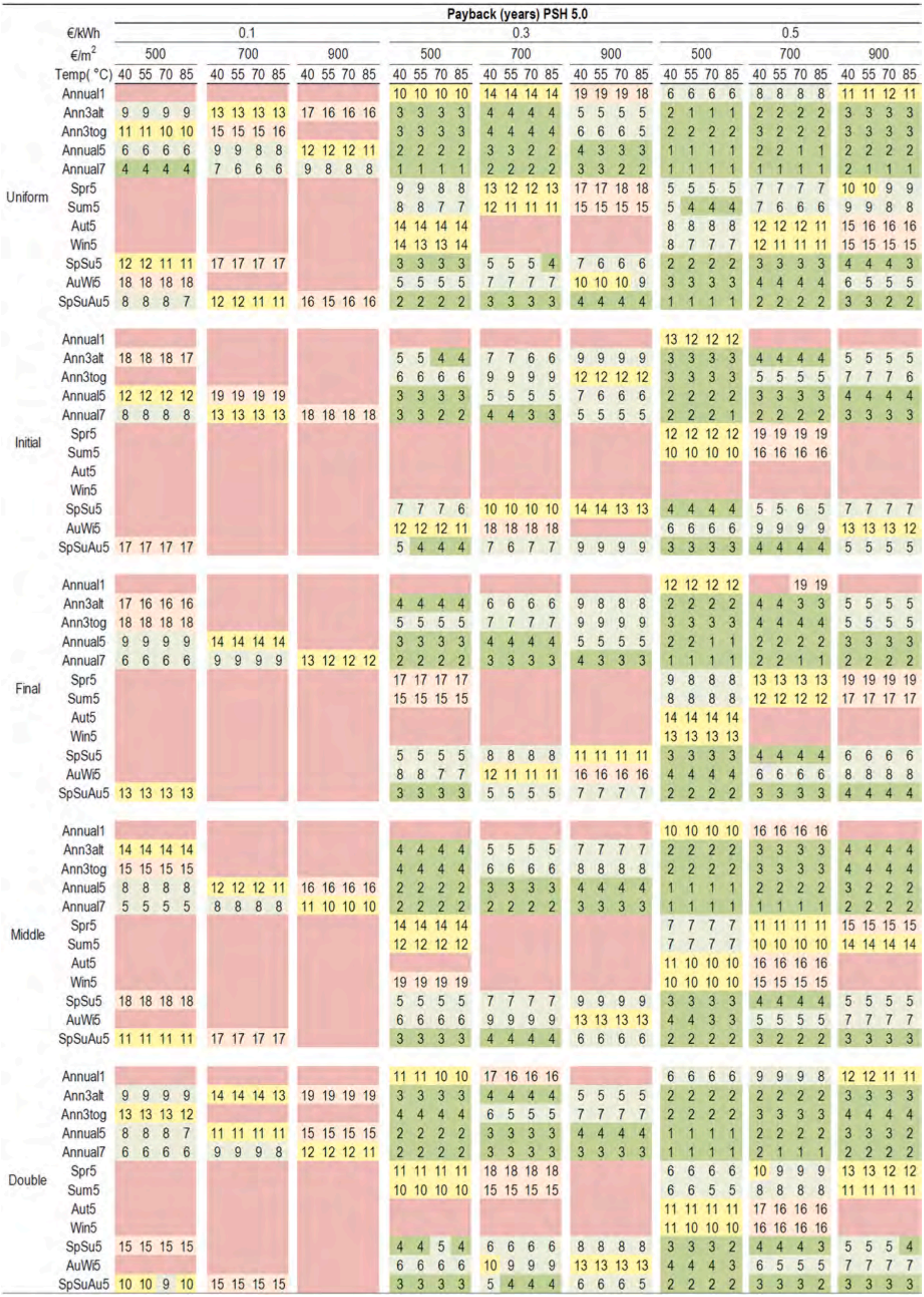
Fig. 4. Payback of the investment made in the optimized SWHS for each scenario, in the location with PSH 3.0. Non-profitable scenarios highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Payback (years) PSH 4.0

	€/kWh	0.1												0.3												0.5											
	€/m^2	500				700				900				500				700				900				500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1													14	13	13	13				19					7	7	8	8	11	11	11	12	15	15	14	14
	Ann3alt	11	11	12	12	16	16	16	16					3	3	3	3	5	5	5	5	6	6	6	6	2	2	2	2	3	3	3	3	4	4	3	4
	Ann3tog	14	14	14	14									4	4	4	4	6	6	6	6	8	8	8	7	3	2	2	2	4	4	3	3	5	5	4	4
	Annual5	8	8	8	7	12	12	11	11	16	16	16	16	2	2	2	2	4	3	3	3	5	5	4	4	2	1	1	1	2	2	2	2	3	3	2	2
	Annual7	6	6	5	5	8	8	8	8	11	11	11	11	2	2	2	2	3	3	2	2	3	3	3	3	1	1	1	1	2	2	2	1	2	2	2	2
	Spr5													10	10	10	10	15	15	15	15					6	6	6	5	8	8	8	8	11	11	11	11
	Sum5													9	9	9	9	13	13	13	13	18	18	18	18	5	5	5	5	8	8	7	7	10	10	10	9
	Aut5																									16	17	17	17								
	Win5																									17	18	17	17								
	SpSu5	13	13	13	13									4	4	4	4	6	5	5	5	7	7	7	7	2	2	2	2	3	3	3	3	4	4	4	4
	AuWi5													9	9	9	9	14	14	14	14	19	19	19	18	5	5	5	5	8	7	7	7	10	10	10	10
	SpSuAu5	10	10	10	9	15	15	15	15					3	3	3	3	4	4	4	4	6	5	5	5	2	2	2	2	3	2	2	2	3	3	3	3
Initial	Annual1																									19	18	17	17								
	Ann3alt													6	6	6	6	9	9	9	9	13	12	12	12	4	3	3	3	5	5	5	5	7	7	6	6
	Ann3tog													8	8	8	8	13	13	12	12	18	17	17	17	5	5	5	4	7	7	7	6	9	9	9	9
	Annual5	17	17	17	17									5	5	5	4	7	7	7	6	9	9	9	8	3	3	3	3	4	4	4	4	5	5	5	5
	Annual7	11	11	11	11	18	18	18	18					3	3	3	3	5	5	5	4	6	6	6	6	2	2	2	2	3	3	3	3	4	4	4	3
	Spr5																									16	15	15	15								
	Sum5																									13	13	12	13								
	Aut5																																				
	Win5																																				
	SpSu5													8	8	8	8	12	12	12	12	17	16	16	16	4	4	4	4	6	6	6	6	9	9	9	8
	AuWi5																									13	13	13	13								
	SpSuAu5													6	6	6	5	9	8	8	8	12	11	11	11	3	3	3	3	5	5	5	5	6	6	6	6
Final	Annual1																									18	18	17	17								
	Ann3alt													6	5	5	5	8	8	8	8	11	11	11	11	3	3	3	3	5	4	4	4	6	6	6	6
	Ann3tog													7	6	6	6	9	9	9	9	13	13	13	13	4	4	3	3	5	5	5	5	7	7	7	7
	Annual5	12	12	12	12	19	19	19	19					4	3	3	3	5	5	5	5	7	7	6	6	2	2	2	2	3	3	3	3	4	4	4	4
	Annual7	8	8	8	8	12	12	12	12	17	17	17	17	3	2	2	2	4	3	3	3	5	5	4	4	2	1	1	1	2	2	2	2	3	3	3	3
	Spr5																									10	10	10	10	16	15	15	15				
	Sum5													19	18	18	18									9	9	9	9	15	14	14	14				
	Aut5																																				
	Win5																																				
	SpSu5													6	6	6	6	9	9	9	9	12	12	12	12	3	3	3	3	5	5	5	5	7	6	6	6
	AuWi5													15	15	15	15									9	8	8	8	12	12	12	12	17	17	17	17
	SpSuAu5	17	16	16	16									4	4	4	4	6	6	6	6	9	8	8	8	3	3	2	2	4	4	3	3	5	5	5	5
Middle	Annual1																									14	14	13	13								
	Ann3alt	18	18	18	18									5	5	5	5	7	7	7	7	9	9	9	9	3	3	3	3	4	4	4	4	5	5	5	5
	Ann3tog													6	5	5	5	8	8	8	8	11	11	11	11	3	3	3	3	5	4	4	4	6	6	6	6
	Annual5	11	10	10	10	16	16	16	16					3	3	3	3	4	4	4	4	6	6	6	5	2	2	2	2	3	3	3	2	3	3	3	3
	Annual7	7	7	7	7	11	10	10	10	15	14	14	14	2	2	2	2	3	3	3	3	4	4	4	4	1	1	1	1	2	2	2	2	2	2	2	2
	Spr5													16	16	16	16									8	8	8	8	13	13	13	13	18	18	18	18
	Sum5													15	15	15	15									8	8	8	8	12	12	12	12	16	17	16	16
	Aut5																																				
	Win5																																				
	SpSu5													5	5	5	5	8	8	8	8	10	10	10	10	3	3	3	3	4	4	4	4	6	6	6	6
	AuWi5													12	12	12	12	19	19	19	19					7	6	6	6	10	10	10	9	13	13	13	13
	SpSuAu5	14	14	14	14									4	4	4	4	6	5	5	5	7	7	7	7	2	2	2	2	3	3	3	3	4	4	4	4
Double	Annual1													15	15	15	15									8	8	8	8	12	12	12	12	17	17	17	16
	Ann3alt	12	12	12	12	19	19	19	19					4	3	3	3	5	5	5	5	7	7	7	7	2	2	2	2	3	3	3	3	4	4	4	4
	Ann3tog	18	18	18	18									5	5	5	5	8	7	7	7	10	10	10	9	3	3	3	3	4	4	4	4	6	6	6	5
	Annual5	11	10	11	10	15	15	15	15					3	3	3	3	5	4	4	4	6	6	6	6	2	2	2	2	3	3	3	3	3	3	3	3
	Annual7	8	8	8	8	12	12	12	11	16	16	16	15	2	2	2	2	3	3	3	3	5	4	4	4	1	1	1	1	2	2	2	2	3	3	2	2
	Spr5													14	14	14	14									8	8	7	7	12	11	11	11	15	15	15	15
	Sum5													12	12	12	12	19	19	19	19					7	7	6	6	10	10	10	9	13	13	13	13
	Aut5																																				
	Win5																																				
	SpSu5	18	18	18	18									5	5	5	5	7	7	7	7	10	10	10	9	3	3	3	3	4	4	4	4	6	5	6	5
	AuWi5													13	12	12	12		19	19	19					8	7	7	6	11	10	10	10	14	14	14	13
	SpSuAu5	13	13	13	12									4	4	4	4	6	6	5	5	7	8	7	7	2	2	2	2	3	3	3	3	4	4	4	4

Fig. 5. Payback of the investment made in the optimized SWHS for each scenario, in the location with PSH 4.0. Non-profitable scenarios highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Payback (years) PSH 5.0

	€/kWh	0.1											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1												
	Ann3alt	9	9	9	9	13	13	13	13	17	16	16	16
	Ann3tog	11	11	10	10	15	15	15	16				
	Annual5	6	6	6	6	9	9	8	8	12	12	12	11
	Annual7	4	4	4	4	7	6	6	6	9	8	8	8
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	12	12	11	11	17	17	17	17				
	AuWi5	18	18	18	18								
	SpSuAu5	8	8	8	7	12	12	11	11	16	15	16	16
Initial	Annual1												
	Ann3alt	18	18	18	17								
	Ann3tog												
	Annual5	12	12	12	12	19	19	19	19				
	Annual7	8	8	8	8	13	13	13	13	18	18	18	18
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	17	17	17	17								
Final	Annual1												
	Ann3alt	17	16	16	16								
	Ann3tog	18	18	18	18								
	Annual5	9	9	9	9	14	14	14	14				
	Annual7	6	6	6	6	9	9	9	9	13	12	12	12
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	13	13	13	13								
Middle	Annual1												
	Ann3alt	14	14	14	14								
	Ann3tog	15	15	15	15								
	Annual5	8	8	8	8	12	12	12	11	16	16	16	16
	Annual7	5	5	5	5	8	8	8	8	11	10	10	10
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	18	18	18	18								
	AuWi5												
	SpSuAu5	11	11	11	11	17	17	17	17				
Double	Annual1												
	Ann3alt	9	9	9	9	14	14	14	13	19	19	19	19
	Ann3tog	13	13	13	12								
	Annual5	8	8	8	7	11	11	11	11	15	15	15	15
	Annual7	6	6	6	6	9	9	9	8	12	12	12	11
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	15	15	15	15								
	AuWi5												
	SpSuAu5	10	10	9	10	15	15	15	15				

	€/kWh	0.3											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1	10	10	10	10	14	14	14	14	19	19	19	18
	Ann3alt	3	3	3	3	4	4	4	4	5	5	5	5
	Ann3tog	3	3	3	3	4	4	4	4	6	6	6	5
	Annual5	2	2	2	2	3	3	2	2	4	3	3	3
	Annual7	1	1	1	1	2	2	2	2	3	3	2	2
	Spr5	9	9	8	8	13	12	12	13	17	17	18	18
	Sum5	8	8	7	7	12	11	11	11	15	15	15	15
	Aut5	14	14	14	14								
	Win5	14	13	13	14								
	SpSu5	3	3	3	3	5	5	5	4	7	6	6	6
	AuWi5	5	5	5	5	7	7	7	7	10	10	10	9
	SpSuAu5	2	2	2	2	3	3	3	3	4	4	4	4
Initial	Annual1												
	Ann3alt	5	5	4	4	7	7	6	6	9	9	9	9
	Ann3tog	6	6	6	6	9	9	9	9	12	12	12	12
	Annual5	3	3	3	3	5	5	5	5	7	6	6	6
	Annual7	3	3	2	2	4	4	3	3	5	5	5	5
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	7	7	7	6	10	10	10	10	14	14	13	13
	AuWi5	12	12	12	11	18	18	18	18				
	SpSuAu5	5	4	4	4	7	6	7	7	9	9	9	9
Final	Annual1												
	Ann3alt	4	4	4	4	6	6	6	6	9	8	8	8
	Ann3tog	5	5	5	5	7	7	7	7	9	9	9	9
	Annual5	3	3	3	3	4	4	4	4	5	5	5	5
	Annual7	2	2	2	2	3	3	3	3	4	3	3	3
	Spr5	17	17	17	17								
	Sum5	15	15	15	15								
	Aut5												
	Win5												
	SpSu5	5	5	5	5	8	8	8	8	11	11	11	11
	AuWi5	8	8	7	7	12	11	11	11	16	16	16	16
	SpSuAu5	3	3	3	3	5	5	5	5	7	7	7	7
Middle	Annual1												
	Ann3alt	4	4	4	4	5	5	5	5	7	7	7	7
	Ann3tog	4	4	4	4	6	6	6	6	8	8	8	8
	Annual5	2	2	2	2	3	3	3	3	4	4	4	4
	Annual7	2	2	2	2	2	2	2	2	3	3	3	3
	Spr5	14	14	14	14								
	Sum5	12	12	12	12								
	Aut5												
	Win5	19	19	19	19								
	SpSu5	5	5	5	5	7	7	7	7	9	9	9	9
	AuWi5	6	6	6	6	9	9	9	9	13	13	13	13
	SpSuAu5	3	3	3	3	4	4	4	4	6	6	6	6
Double	Annual1	11	11	10	10	17	16	16	16				
	Ann3alt	3	3	3	3	4	4	4	4	5	5	5	5
	Ann3tog	4	4	4	4	6	5	5	5	7	7	7	7
	Annual5	2	2	2	2	3	3	3	3	4	4	4	4
	Annual7	2	2	2	2	3	3	3	3	3	3	3	3
	Spr5	11	11	11	11	18	18	18	18				
	Sum5	10	10	10	10	15	15	15	15				
	Aut5												
	Win5												
	SpSu5	4	4	5	4	6	6	6	6	8	8	8	8
	AuWi5	6	6	6	6	10	9	9	9	13	13	13	13
	SpSuAu5	3	3	3	3	5	4	4	4	6	6	6	5

	€/kWh	0.5											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1	6	6	6	6	8	8	8	8	11	11	12	11
	Ann3alt	2	1	1	1	2	2	2	2	3	3	3	3
	Ann3tog	2	2	2	2	3	2	2	2	3	3	3	3
	Annual5	1	1	1	1	2	2	1	1	2	2	2	2
	Annual7	1	1	1	1	1	1	1	1	2	1	1	1
	Spr5	5	5	5	5	7	7	7	7	10	10	9	9
	Sum5	5	4	4	4	7	6	6	6	9	9	8	8
	Aut5	8	8	8	8	12	12	12	11	15	16	16	16
	Win5	8	7	7	7	12	11	11	11	15	15	15	15
	SpSu5	2	2	2	2	3	3	3	3	4	4	4	3
	AuWi5	3	3	3	3	4	4	4	4	6	5	5	5
	SpSuAu5	1	1	1	1	2	2	2	2	3	3	2	2
Initial	Annual1	13	12	12	12								
	Ann3alt	3	3	3	3	4	4	4	4	5	5	5	5
	Ann3tog	3	3	3	3	5	5	5	5	7	7	7	6
	Annual5	2	2	2	2	3	3	3	3	4	4	4	4
	Annual7	2	2	2	1	2	2	2	2	3	3	3	3
	Spr5	12	12	12	12	19	19	19	19				
	Sum5	10	10	10	10	16	16	16	16				
	Aut5												
	Win5												
	SpSu5	4	4	4	4	5	5	6	5	7	7	7	7
	AuWi5	6	6	6	6	9	9	9	9	13	13	13	12
	SpSuAu5	3	3	3	3	4	4	4	4	5	5	5	5
Final	Annual1	12	12	12	12			19	19				
	Ann3alt	2	2	2	2	4	4	3	3	5	5	5	5
	Ann3tog	3	3	3	3	4	4	4	4	5	5	5	5
	Annual5	2	2	1	1	2	2	2	2	3	3	3	3
	Annual7	1	1	1	1	2	2	1	1	2	2	2	2
	Spr5	9	8	8	8	13	13	13	13	19	19	19	19
	Sum5	8	8	8	8	12	12	12	12	17	17	17	17
	Aut5	14	14	14	14								
	Win5	13	13	13	13								
	SpSu5	3	3	3	3	4	4	4	4	6	6	6	6
	AuWi5	4	4	4	4	6	6	6	6	8	8	8	8
	SpSuAu5	2	2	2	2	3	3	3	3	4	4	4	4
Middle	Annual1	10	10	10	10	16	16	16	16				
	Ann3alt	2	2	2	2	3	3	3	3	4	4	4	4
	Ann3tog	2	2	2	2	3	3	3	3	4	4	4	4
	Annual5	1	1	1	1	2	2	2	2	3	2	2	2
	Annual7	1	1	1	1	1	1	1	1	2	2	2	2
	Spr5	7	7	7	7	11	11	11	11	15	15	15	15
	Sum5	7	7	7	7	10	10	10	10	14	14	14	14
	Aut5	11	10	10	10	16	16	16	16				
	Win5	10	10	10	10	15	15	15	15				
	SpSu5	3	3	3	3	4	4	4	4	5	5	5	5
	AuWi5	4	4	3	3	5	5	5	5	7	7	7	7
	SpSuAu5	2	2	2	2	3	2	2	2	3	3	3	3
Double	Annual1	6	6	6	6	9	9	9	8	12	12	11	11
	Ann3alt	2	2	2	2	2	2	2	2	3	3	3	3
	Ann3tog	2	2	2	2	3	3	3	3	4	4	4	4
	Annual5	1	1	1	1	2	2	2	2	3	3	3	2
	Annual7	1	1	1	1	2	1	1	1	2	2	2	2
	Spr5	6	6	6	6	10	9	9	9	13	13	12	12
	Sum5	6	6	5	5	8	8	8	8	11	11	11	11
	Aut5	11	11	11	11	17	16	16	16				
	Win5	11	10	10	10	16	16	16	16				
	SpSu5	3	3	3	2	4	4	4	3	5	5	5	4
	AuWi5	4	4	4	3	6	5	5	5	7	7	7	7
	SpSuAu5	2	2	2	2	3	3	3	2	3	3	3	3

Fig. 6. Payback of the investment made in the optimized SWHS for each scenario, in the location with PSH 5.0. Non-profitable scenarios highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

optimized SWHS. Each one presents a summary of the 2160 scenarios analyzed for each location, combining the proposed patterns (frequency, seasonality, and water temperature) with different contexts (energy prices and required investment). The purpose is to provide the sector with a comprehensive view of the profitability of SWHS to assist in decision-making. A specific industry can estimate the viability of implementing SWHS based on the similarity of their consumption patterns and specific context. Subsequently, some significant results are detailed.

3.1.1. *Daily pattern*

The daily demand pattern influences the number of scenarios in which SWHS is financially viable. The “Uniform” pattern is the most favorable for the implementation of SWHS, proving viable in 66 % of the analyzed scenarios. At the opposite end, the “Initial” pattern is profitable in 41 % of scenarios. The “Double”, “Middle”, and “Final” patterns exhibit percentages of 58 %, 53 %, and 48 %, respectively.

The daily pattern not only determines the number of profitable scenarios but also affects the profitability achieved in each of them. The payback period can potentially double with the “Initial” pattern compared to the “Uniform” pattern. As they are not profitable in the same number of scenarios, the average value across all cases introduces some distortion, with elevated values in extreme cases that increase the mean for more favorable patterns. Considering a standard comparison framework where all scenarios are profitable (Annual7 and PSH 5.0), the average payback is 3 years for the “Uniform” pattern, 6.3 years for the “Initial”, 4.4 years for the “Final”, 3.8 years for the “Middle”, and 4.3 years for the “Double” pattern.

3.1.2. *Weekly pattern*

Similarly, the weekly consumption frequency strongly influences the number of scenarios in which SWHS can be profitable, as well as the payback period of the required investment. With a uniform daily pattern, consuming only one day per week significantly penalises the feasibility of SWHS, being profitable in only 24 % of the proposed scenarios, the most favorable ones. Increasing the consumption to Mondays, Wednesdays, and Fridays substantially enhances the viability of SWHS (79 % of scenarios) due to the energy storage capacity in the tank. Consumption limited to three consecutive days slightly reduces viability compared to alternate days, with 71 %. In the common case of demand from Monday to Friday, SWHS are profitable in a large portion of the analyzed scenarios (87 %), except for locations with low radiation and low energy prices. In the most favorable pattern with demand all seven days of the week, the solar system is viable in the vast majority of scenarios (96 %).

Even in profitable scenarios, the payback period is unappealing with a one-day pattern. Thus, the mode presents a value of 12 years for the one-day pattern, five for three alternate days, four for three consecutive days, three for five days, and two for seven days. In a comparison framework with all profitable cases (extremely favorable scenarios with €500/m^2, 50c€/kWh, and PSH 5.0), the average payback with one day of consumption would be 9 years, reducing to 2 for three-day patterns, and 1 for five and seven days.

3.1.3. *Seasonality*

Regarding seasonality, SWHS tends not to be viable in industries with a strong concentration in a few months, especially in autumn and winter. Exclusive demand in summer or spring also limits the feasibility of SWHS. At least half a year of demand and consumption for five days a week is needed to achieve profitability values close to those of annual demand with lower weekly frequency. In the most favorable seasonality pattern, with demand throughout the year except for winter, the obtained paybacks are similar to the equivalent pattern without seasonality.

Considering the set of analyzed scenarios, demand concentrated in autumn or winter limits the viability of SWHS to less than 10 % of scenarios. If concentrated in spring or summer, it increases to 33 % and 41 %, respectively. As the months of demand increase, the percentage reaches 71 % by combining spring and summer, and 79 % with demand throughout the year except for winter.

3.1.4. *Demanded temperature*

The demanded water temperature barely affects the profitability of the optimized SWHS. The criterion of maximizing the “Savings/Payback” ratio tends to converge on similar values for equivalent scenarios. The small variations between them are due to rounding to the nearest unit and differences in installation size. However, where the demanded temperature does have a significant impact is on the required collector surface area. Maintaining the same volume of daily water, an increase in temperature results in a growing need for energy for heating. Consider Fig. 7 as an illustrative example, depicting the outcomes for the optimal number of collectors in the case of PSH 4.0. The results for the remaining two locations have not been included since the size of the installation depends on the required volume and temperature, making it not applicable as a reference for other cases.

3.1.5. *Context*

The previous discussions focus on patterns, considering the set of proposed scenarios. However, contextual variables strongly influence the viability of SWHS.

The energy price is a key parameter. In an energy context like that of a few years ago, with a very low energy price, the viability of SWHS is severely compromised. It achieves attractive returns in a limited number of cases with the most uniform patterns and other favorable variables. Conversely, if energy prices in recent years persist in the future, the investment in SWHS becomes highly attractive in a large number of scenarios, even in locations with low radiation. In the most favorable scenarios, with only one or two years of disproportionately high energy prices (as recorded in some cases in 2022), SWHS could pay off.

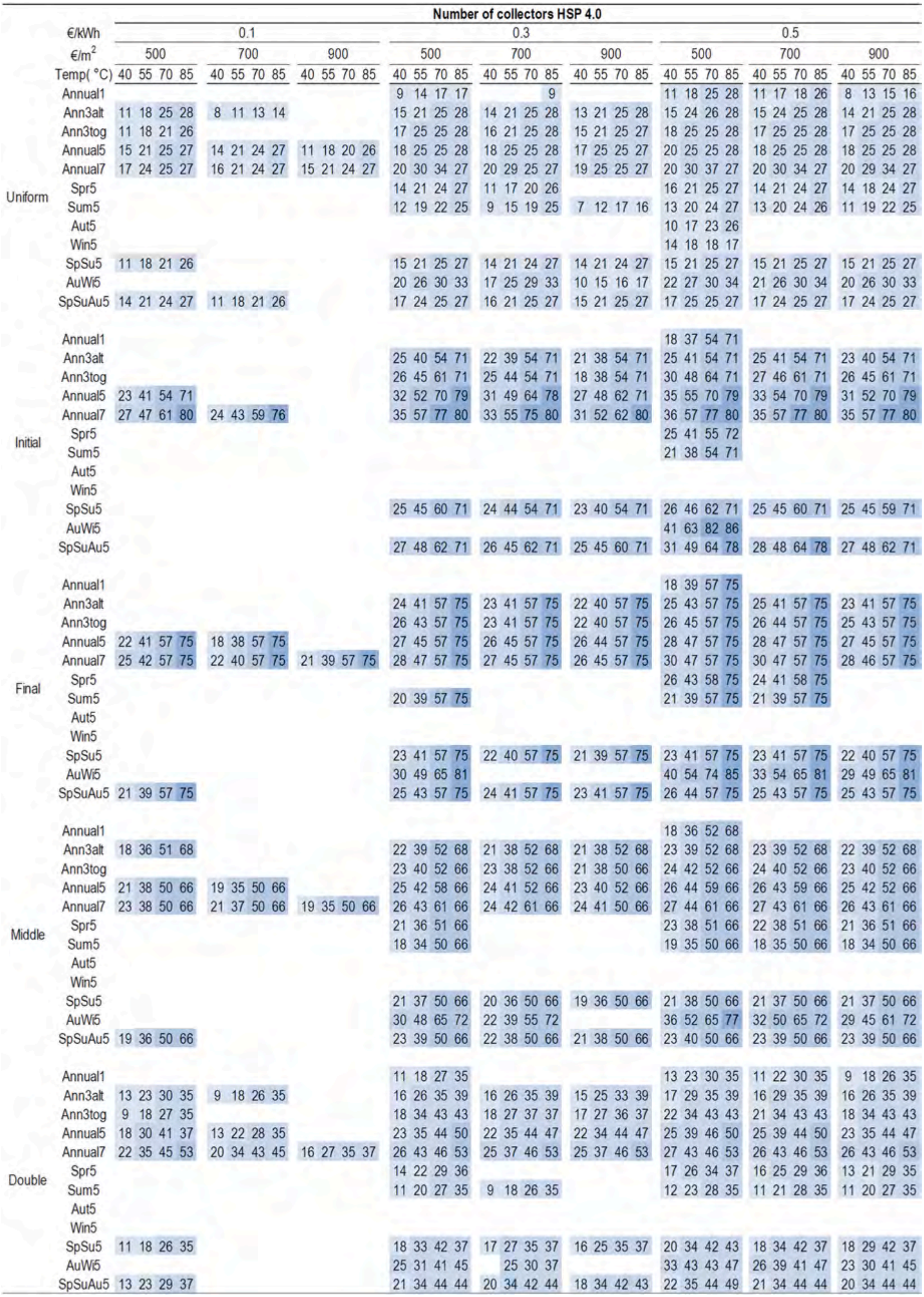
Irradiance also plays a crucial role in implementing a solar system. The number of profitable scenarios increases from 43 % to 63 % when moving from 3.0 PSH to 5.0 PSH. The analyzed range of investment prices also causes significant variations in profitability. The mode of the payback for the set of profitable cases is 3 years for 500 €/m^2, 4 years for 700 €/m^2, and 5 years for 900 €/m^2.

The results are consistent with those obtained in previous studies in industries with specific consumption patterns. For example, in a medium-sized meat industry with 5-day work shifts, demand distributed throughout the day but higher in the late afternoon hours, intermediate radiation (4.0 PSH), and an energy price of 0.3 €/kWh, payback periods between 2 and 4 years were obtained depending on the investment cost [19]. In a previous study with the same pattern but analyzing only low energy prices between 5 and 20 c€/kW (electricity, gas, and diesel), payback periods ranged from 7 to more than 20 years, depending on the city’s radiation and national energy prices [12]. In a study in the wine industry, considering energy prices of 30 c€/kWh and intermediate radiation, the payback ranged from 2 to 7 years in a large winery with relatively uniform demand during 73 % of the days of the year (equivalent to 5 days per week), between 5 and 10 years in a medium-sized winery with demand on 58 % of the days (slightly over 3 days per week), and over 12 years with most scenarios being unprofitable in a small winery with very irregular demand during 19 % of the days of the year (equivalent to 1 day per week) [15].

3.2. *Savings*

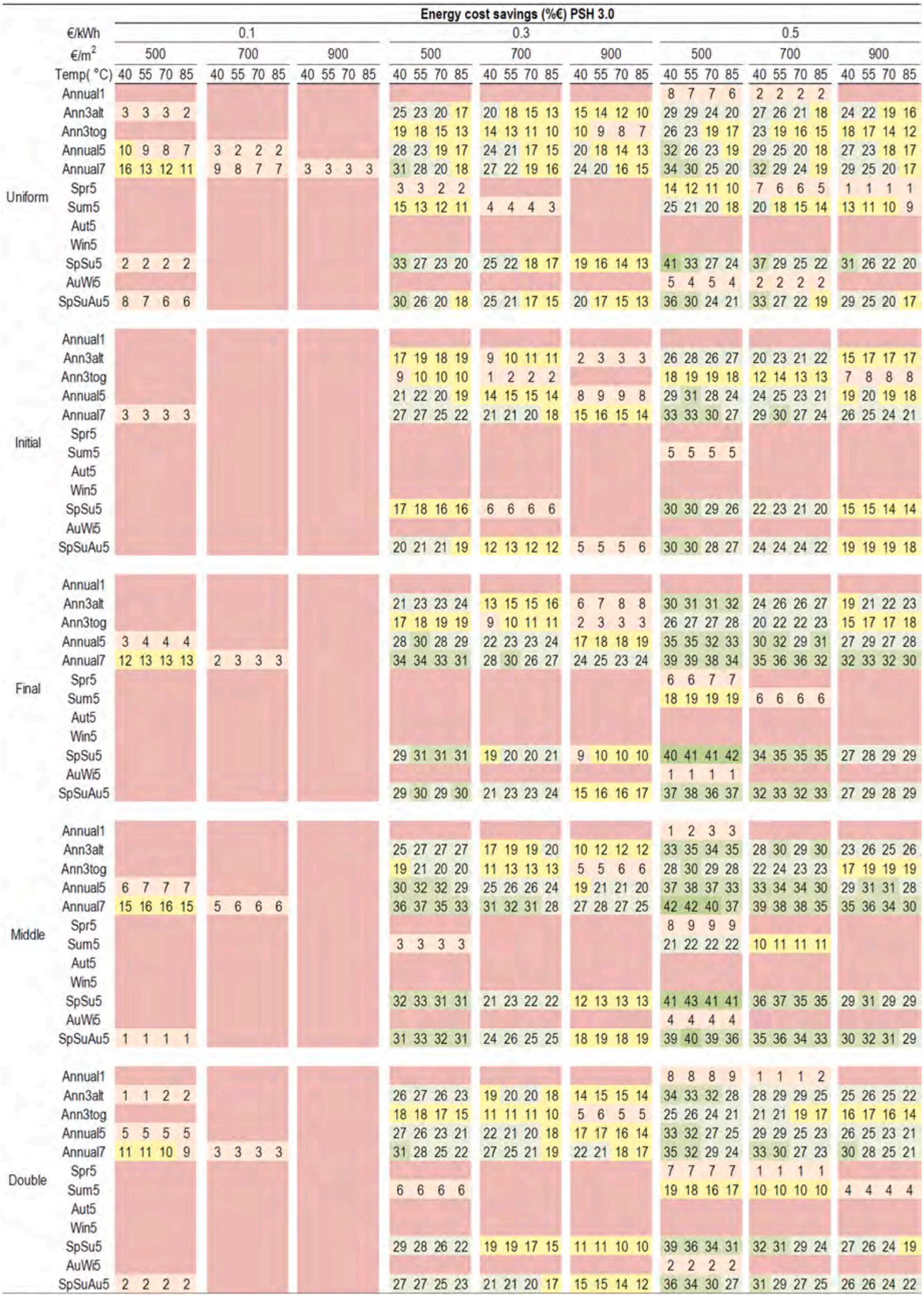
3.2.1. *Energy cost savings*

An attractive payback on the investment is not always synonymous with significant savings in the total energy cost during the SWHS’s useful life (including the investment). In many scenarios, the pursuit of high profitability limits the achievable savings. Fig. 8 (results for PSH 3.0), Fig. 9 (results for PSH 4.0) and Fig. 10 (results for PSH 5.0) detail the



		Number of collectors HSP 4.0																																			
	€/kWh	0.1												0.3												0.5											
	€/m^2	500				700				900				500				700				900				500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1													9	14	17	17				9					11	18	25	28	11	17	18	26	8	13	15	16
	Ann3alt	11	18	25	28	8	11	13	14					15	21	25	28	14	21	25	28	13	21	25	28	15	24	26	28	15	24	25	28	14	21	25	28
	Ann3tog	11	18	21	26									17	25	25	28	16	21	25	28	15	21	25	27	18	25	25	28	17	25	25	28	17	25	25	28
	Annual5	15	21	25	27	14	21	24	27	11	18	20	26	18	25	25	28	18	25	25	28	17	25	25	27	20	25	25	28	18	25	25	28	18	25	25	28
	Annual7	17	24	25	27	16	21	24	27	15	21	24	27	20	30	34	27	20	29	25	27	19	25	25	27	20	30	37	27	20	30	34	27	20	29	34	27
	Spr5													14	21	24	27	11	17	20	26					16	21	25	27	14	21	24	27	14	18	24	27
	Sum5													12	19	22	25	9	15	19	25	7	12	17	16	13	20	24	27	13	20	24	26	11	19	22	25
	Aut5																									10	17	23	26								
	Win5																									14	18	18	17								
	SpSu5	11	18	21	26									15	21	25	27	14	21	24	27	14	21	24	27	15	21	25	27	15	21	25	27	15	21	25	27
	AuWi5													20	26	30	33	17	25	29	33	10	15	16	17	22	27	30	34	21	26	30	34	20	26	30	33
	SpSuAu5	14	21	24	27	11	18	21	26					17	24	25	27	16	21	25	27	15	21	25	27	17	25	25	27	17	24	25	27	17	24	25	27
Initial	Annual1																									18	37	54	71								
	Ann3alt													25	40	54	71	22	39	54	71	21	38	54	71	25	41	54	71	25	41	54	71	23	40	54	71
	Ann3tog													26	45	61	71	25	44	54	71	18	38	54	71	30	48	64	71	27	46	61	71	26	45	61	71
	Annual5	23	41	54	71									32	52	70	79	31	49	64	78	27	48	62	71	35	55	70	79	33	54	70	79	31	52	70	79
	Annual7	27	47	61	80	24	43	59	76					35	57	77	80	33	55	75	80	31	52	62	80	36	57	77	80	35	57	77	80	35	57	77	80
	Spr5																									25	41	55	72								
	Sum5																									21	38	54	71								
	Aut5																																				
	Win5																																				
	SpSu5													25	45	60	71	24	44	54	71	23	40	54	71	26	46	62	71	25	45	60	71	25	45	59	71
	AuWi5																									41	63	82	86								
	SpSuAu5													27	48	62	71	26	45	62	71	25	45	60	71	31	49	64	78	28	48	64	78	27	48	62	71
Final	Annual1																									18	39	57	75								
	Ann3alt													24	41	57	75	23	41	57	75	22	40	57	75	25	43	57	75	25	41	57	75	23	41	57	75
	Ann3tog													26	43	57	75	23	41	57	75	22	40	57	75	26	45	57	75	26	44	57	75	25	43	57	75
	Annual5	22	41	57	75	18	38	57	75					27	45	57	75	26	45	57	75	26	44	57	75	28	47	57	75	28	47	57	75	27	45	57	75
	Annual7	25	42	57	75	22	40	57	75	21	39	57	75	28	47	57	75	27	45	57	75	26	45	57	75	30	47	57	75	30	47	57	75	28	46	57	75
	Spr5																									26	43	58	75	24	41	58	75				
	Sum5													20	39	57	75									21	39	57	75	21	39	57	75				
	Aut5																																				
	Win5																																				
	SpSu5													23	41	57	75	22	40	57	75	21	39	57	75	23	41	57	75	23	41	57	75	22	40	57	75
	AuWi5													30	49	65	81									40	54	74	85	33	54	65	81	29	49	65	81
	SpSuAu5	21	39	57	75									25	43	57	75	24	41	57	75	23	41	57	75	26	44	57	75	25	43	57	75	25	43	57	75
Middle	Annual1																									18	36	52	68								
	Ann3alt	18	36	51	68									22	39	52	68	21	38	52	68	21	38	52	68	23	39	52	68	23	39	52	68	22	39	52	68
	Ann3tog													23	40	52	66	23	38	52	66	21	38	50	66	24	42	52	66	24	40	52	66	23	40	52	66
	Annual5	21	38	50	66	19	35	50	66					25	42	58	66	24	41	52	66	23	40	52	66	26	44	59	66	26	43	59	66	25	42	52	66
	Annual7	23	38	50	66	21	37	50	66	19	35	50	66	26	43	61	66	24	42	61	66	24	41	50	66	27	44	61	66	27	43	61	66	26	43	61	66
	Spr5													21	36	51	66									23	38	51	66	22	38	51	66	21	36	51	66
	Sum5													18	34	50	66									19	35	50	66	18	35	50	66	18	34	50	66
	Aut5																																				
	Win5																																				
	SpSu5													21	37	50	66	20	36	50	66	19	36	50	66	21	38	50	66	21	37	50	66	21	37	50	66
	AuWi5													30	48	65	72	22	39	55	72					36	52	65	77	32	50	65	72	29	45	61	72
	SpSuAu5	19	36	50	66									23	39	50	66	22	38	50	66	21	38	50	66	23	40	50	66	23	39	50	66	23	39	50	66
Double	Annual1													11	18	27	35									13	23	30	35	11	22	30	35	9	18	26	35
	Ann3alt	13	23	30	35	9	18	26	35					16	26	35	39	16	26	35	39	15	25	33	39	17	29	35	39	16	29	35	39	16	26	35	39
	Ann3tog	9	18	27	35									18	34	43	43	18	27	37	37	17	27	36	37	22	34	43	43	21	34	43	43	18	34	43	43
	Annual5	18	30	41	37	13	22	28	35					23	35	44	50	22	35	44	47	22	34	44	47	25	39	46	50	25	39	44	50	23	35	44	47
	Annual7	22	35	45	53	20	34	43	45	16	27	35	37	26	43	46	53	25	37	46	53	25	37	46	53	27	43	46	53	26	43	46	53	26	43	46	53
	Spr5													14	22	29	36									17	26	34	37	16	25	29	36	13	21	29	35
	Sum5													11	20	27	35	9	18	26	35					12	23	28	35	11	21	28	35	11	20	27	35
	Aut5																																				
	Win5																																				
	SpSu5	11	18	26	35									18	33	42	37	17	27	35	37	16	25	35	37	20	34	42	43	18	34	42	37	18	29	42	37
	AuWi5													25	31	41	45		25	30	37					33	43	43	47	26	39	41	47	23	30	41	45
	SpSuAu5	13	23	29	37									21	34	44	44	20	34	42	44	18	34	42	43	22	35	44	49	21	34	44	44	20	34	44	44

Fig. 7. Number of 2 m^2 solar collectors that optimize the “Savings/Payback” ratio in the location with PSH 4.0.



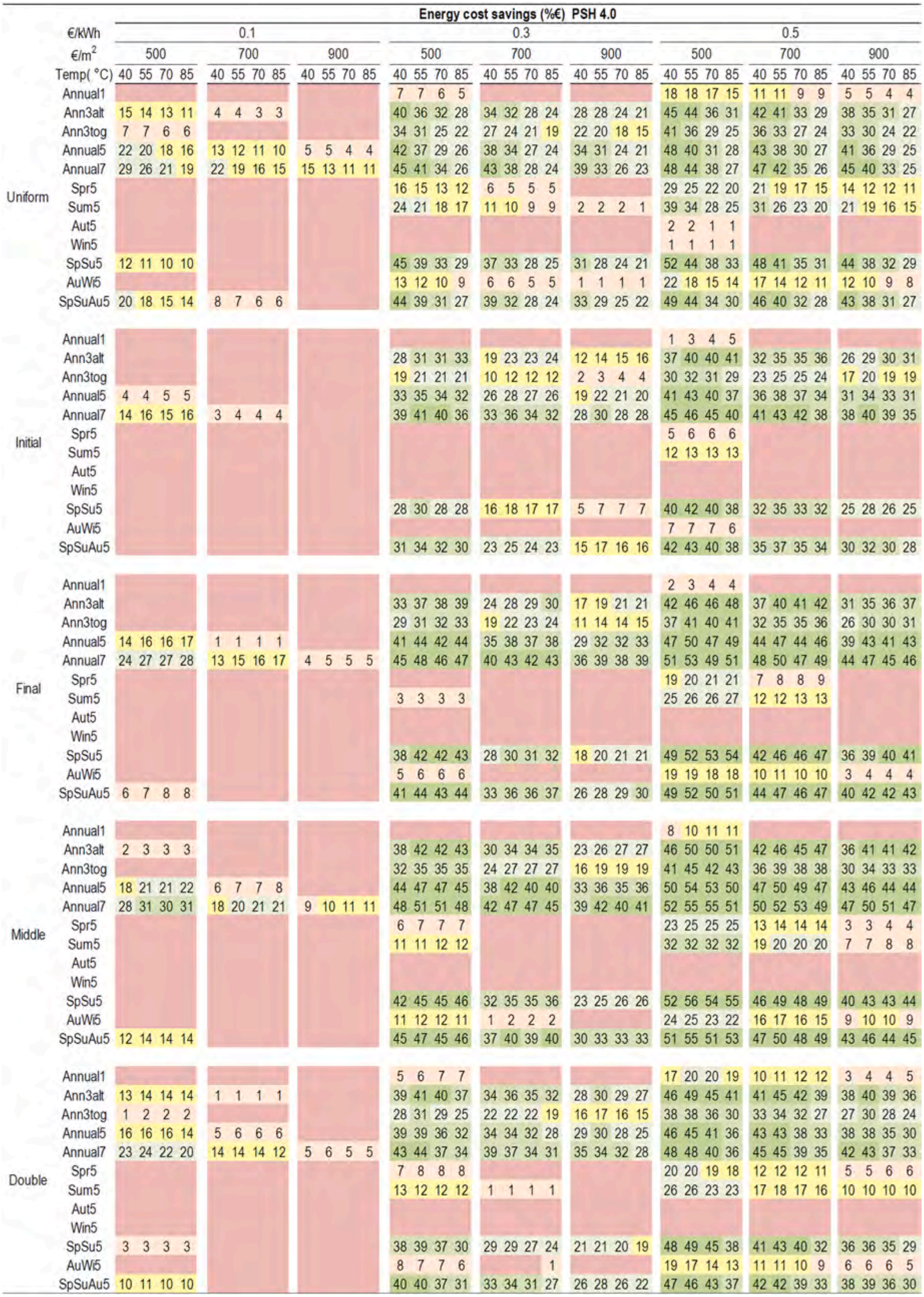
Energy cost savings (%€) PSH 3.0

	€/kWh	0.1											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1												
	Ann3alt	3	3	3	2								
	Ann3tog												
	Annual5	10	9	8	7	3	2	2	2				
	Annual7	16	13	12	11	9	8	7	7	3	3	3	3
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	2	2	2	2								
	AuWi5												
	SpSuAu5	8	7	6	6								
Initial	Annual1												
	Ann3alt												
	Ann3tog												
	Annual5												
	Annual7	3	3	3	3								
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5												
Final	Annual1												
	Ann3alt												
	Ann3tog												
	Annual5	3	4	4	4								
	Annual7	12	13	13	13	2	3	3	3				
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5												
Middle	Annual1												
	Ann3alt												
	Ann3tog												
	Annual5	6	7	7	7								
	Annual7	15	16	16	15	5	6	6	6				
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	1	1	1	1								
Double	Annual1												
	Ann3alt	1	1	2	2								
	Ann3tog												
	Annual5	5	5	5	5								
	Annual7	11	11	10	9	3	3	3	3				
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	2	2	2	2								

	€/kWh	0.3											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1												
	Ann3alt	25	23	20	17	20	18	15	13	15	14	12	10
	Ann3tog	19	18	15	13	14	13	11	10	10	9	8	7
	Annual5	28	23	19	17	24	21	17	15	20	18	14	13
	Annual7	31	28	20	18	27	22	19	16	24	20	16	15
	Spr5	3	3	2	2								
	Sum5	15	13	12	11	4	4	4	3				
	Aut5												
	Win5												
	SpSu5	33	27	23	20	25	22	18	17	19	16	14	13
	AuWi5												
	SpSuAu5	30	26	20	18	25	21	17	15	20	17	15	13
Initial	Annual1												
	Ann3alt	17	19	18	19	9	10	11	11	2	3	3	3
	Ann3tog	9	10	10	10	1	2	2	2				
	Annual5	21	22	20	19	14	15	15	14	8	9	9	8
	Annual7	27	27	25	22	21	21	20	18	15	16	15	14
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	17	18	16	16	6	6	6	6				
	AuWi5												
	SpSuAu5	20	21	21	19	12	13	12	12	5	5	5	6
Final	Annual1												
	Ann3alt	21	23	23	24	13	15	15	16	6	7	8	8
	Ann3tog	17	18	19	19	9	10	11	11	2	3	3	3
	Annual5	28	30	28	29	22	23	23	24	17	18	18	19
	Annual7	34	34	33	31	28	30	26	27	24	25	23	24
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	29	31	31	31	19	20	20	21	9	10	10	10
	AuWi5												
	SpSuAu5	29	30	29	30	21	23	23	24	15	16	16	17
Middle	Annual1												
	Ann3alt	25	27	27	27	17	19	19	20	10	12	12	12
	Ann3tog	19	21	20	20	11	13	13	13	5	5	6	6
	Annual5	30	32	32	29	25	26	26	24	19	21	21	20
	Annual7	36	37	35	33	31	32	31	28	27	28	27	25
	Spr5												
	Sum5	3	3	3	3								
	Aut5												
	Win5												
	SpSu5	32	33	31	31	21	23	22	22	12	13	13	13
	AuWi5												
	SpSuAu5	31	33	32	31	24	26	25	25	18	19	18	19
Double	Annual1												
	Ann3alt	26	27	26	23	19	20	20	18	14	15	15	14
	Ann3tog	18	18	17	15	11	11	11	10	5	6	5	5
	Annual5	27	26	23	21	22	21	20	18	17	17	16	14
	Annual7	31	28	25	22	27	25	21	19	22	21	18	17
	Spr5												
	Sum5	6	6	6	6								
	Aut5												
	Win5												
	SpSu5	29	28	26	22	19	19	17	15	11	11	10	10
	AuWi5												
	SpSuAu5	27	27	25	23	21	21	20	17	15	15	14	12

	€/kWh	0.5											
	€/m^2	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1	8	7	7	6	2	2	2	2				
	Ann3alt	29	29	24	20	27	26	21	18	24	22	19	16
	Ann3tog	26	23	19	17	23	19	16	15	18	17	14	12
	Annual5	32	26	23	19	29	25	20	18	27	23	18	17
	Annual7	34	30	25	20	32	29	24	19	29	25	20	17
	Spr5	14	12	11	10	7	6	6	5	1	1	1	1
	Sum5	25	21	20	18	20	18	15	14	13	11	10	9
	Aut5												
	Win5												
	SpSu5	41	33	27	24	37	29	25	22	31	26	22	20
	AuWi5	5	4	5	4	2	2	2	2				
	SpSuAu5	36	30	24	21	33	27	22	19	29	25	20	17
Initial	Annual1												
	Ann3alt	26	28	26	27	20	23	21	22	15	17	17	17
	Ann3tog	18	19	19	18	12	14	13	13	7	8	8	8
	Annual5	29	31	28	24	24	25	23	21	19	20	19	18
	Annual7	33	33	30	27	29	30	27	24	26	25	24	21
	Spr5												
	Sum5	5	5	5	5								
	Aut5												
	Win5												
	SpSu5	30	30	29	26	22	23	21	20	15	15	14	14
	AuWi5												
	SpSuAu5	30	30	28	27	24	24	24	22	19	19	19	18
Final	Annual1												
	Ann3alt	30	31	31	32	24	26	26	27	19	21	22	23
	Ann3tog	26	27	27	28	20	22	22	23	15	17	17	18
	Annual5	35	35	32	33	30	32	29	31	27	29	27	28
	Annual7	39	39	38	34	35	36	36	32	32	33	32	30
	Spr5	6	6	7	7								
	Sum5	18	19	19	19	6	6	6	6				
	Aut5												
	Win5												
	SpSu5	40	41	41	42	34	35	35	35	27	28	29	29
	AuWi5	1	1	1	1								
	SpSuAu5	37	38	36	37	32	33	32	33	27	29	28	29
Middle	Annual1	1	2	3	3								
	Ann3alt	33	35	34	35	28	30	29	30	23	26	25	26
	Ann3tog	28	30	29	28	22	24	23	23	17	19	19	19
	Annual5	37	38	37	33	33	34	34	30	29	31	31	28
	Annual7	42	42	40	37	39	38	38	35	35	36	34	30
	Spr5	8	9	9	9								
	Sum5	21	22	22	22	10	11	11	11				
	Aut5												
	Win5												
	SpSu5	41	43	41	41	36	37	35	35	29	31	29	29
	AuWi5	4	4	4	4								
	SpSuAu5	39	40	39	36	35	36	34	33	30	32	31	29
Double	Annual1	8	8	8	9	1	1	1	2				
	Ann3alt	34	33	32	28	28	29	29	25	25	26	25	22
	Ann3tog	25	26	24	21	21	21	19	17	16	17	16	14
	Annual5	33	32	27	25	29	29	25	23	26	25	23	21
	Annual7	35	32	29	24	33	30	27	23	30	28	25	21
	Spr5	7	7	7	7	1	1	1	1				
	Sum5	19	18	16	17	10	10	10	10	4	4	4	4
	Aut5												
	Win5												
	SpSu5	39	36	34	31	32	31	29	24	27	26	24	19
	AuWi5	2	2	2	2								
	SpSuAu5	36	34	30	27	31	29	27	25	26	26	24	22

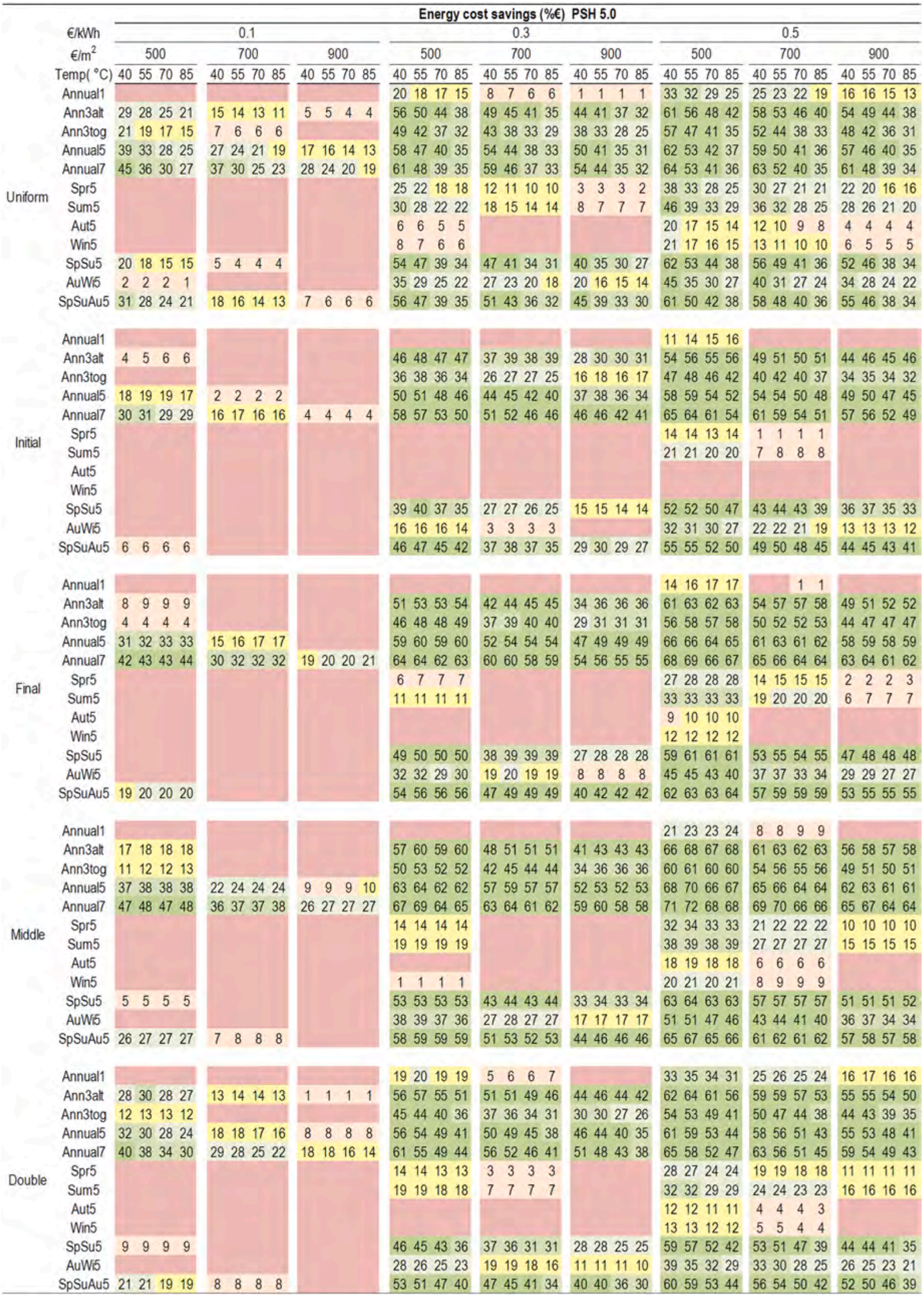
Fig. 8. Cumulative Energy Cost Savings over 20 Years (Including Investment Costs) compared to the scenario without SWHS, in the location with PSH 3.0.



Energy cost savings (%€) PSH 4.0

	€/kWh	0.1												0.3												0.5											
	€/m^2	500				700				900				500				700				900				500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1													7	7	6	5									18	18	17	15	11	11	9	9	5	5	4	4
	Ann3alt	15	14	13	11	4	4	3	3					40	36	32	28	34	32	28	24	28	28	24	21	45	44	36	31	42	41	33	29	38	35	31	27
	Ann3tog	7	7	6	6									34	31	25	22	27	24	21	19	22	20	18	15	41	36	29	25	36	33	27	24	33	30	24	22
	Annual5	22	20	18	16	13	12	11	10	5	5	4	4	42	37	29	26	38	34	27	24	34	31	24	21	48	40	31	28	43	38	30	27	41	36	29	25
	Annual7	29	26	21	19	22	19	16	15	15	13	11	11	45	41	34	26	43	38	28	24	39	33	26	23	48	44	38	27	47	42	35	26	45	40	33	25
	Spr5													16	15	13	12	6	5	5	5					29	25	22	20	21	19	17	15	14	12	12	11
	Sum5													24	21	18	17	11	10	9	9	2	2	2	1	39	34	28	25	31	26	23	20	21	19	16	15
	Aut5																									2	2	1	1								
	Win5																									1	1	1	1								
	SpSu5	12	11	10	10									45	39	33	29	37	33	28	25	31	28	24	21	52	44	38	33	48	41	35	31	44	38	32	29
	AuWi5													13	12	10	9	6	6	5	5	1	1	1	1	22	18	15	14	17	14	12	11	12	10	9	8
	SpSuAu5	20	18	15	14	8	7	6	6					44	39	31	27	39	32	28	24	33	29	25	22	49	44	34	30	46	40	32	28	43	38	31	27
Initial	Annual1																									1	3	4	5								
	Ann3alt													28	31	31	33	19	23	23	24	12	14	15	16	37	40	40	41	32	35	35	36	26	29	30	31
	Ann3tog													19	21	21	21	10	12	12	12	2	3	4	4	30	32	31	29	23	25	25	24	17	20	19	19
	Annual5	4	4	5	5									33	35	34	32	26	28	27	26	19	22	21	20	41	43	40	37	36	38	37	34	31	34	33	31
	Annual7	14	16	15	16	3	4	4	4					39	41	40	36	33	36	34	32	28	30	28	28	45	46	45	40	41	43	42	38	38	40	39	35
	Spr5																									5	6	6	6								
	Sum5																									12	13	13	13								
	Aut5																																				
	Win5																																				
	SpSu5													28	30	28	28	16	18	17	17	5	7	7	7	40	42	40	38	32	35	33	32	25	28	26	25
	AuWi5																									7	7	7	6								
	SpSuAu5													31	34	32	30	23	25	24	23	15	17	16	16	42	43	40	38	35	37	35	34	30	32	30	28
Final	Annual1																									2	3	4	4								
	Ann3alt													33	37	38	39	24	28	29	30	17	19	21	21	42	46	46	48	37	40	41	42	31	35	36	37
	Ann3tog													29	31	32	33	19	22	23	24	11	14	14	15	37	41	40	41	32	35	35	36	26	30	30	31
	Annual5	14	16	16	17	1	1	1	1					41	44	42	44	35	38	37	38	29	32	32	33	47	50	47	49	44	47	44	46	39	43	41	43
	Annual7	24	27	27	28	13	15	16	17	4	5	5	5	45	48	46	47	40	43	42	43	36	39	38	39	51	53	49	51	48	50	47	49	44	47	45	46
	Spr5																									19	20	21	21	7	8	8	9				
	Sum5													3	3	3	3									25	26	26	27	12	12	13	13				
	Aut5																																				
	Win5																																				
	SpSu5													38	42	42	43	28	30	31	32	18	20	21	21	49	52	53	54	42	46	46	47	36	39	40	41
	AuWi5													5	6	6	6									19	19	18	18	10	11	10	10	3	4	4	4
	SpSuAu5	6	7	8	8									41	44	43	44	33	36	36	37	26	28	29	30	49	52	50	51	44	47	46	47	40	42	42	43
Middle	Annual1																									8	10	11	11								
	Ann3alt	2	3	3	3									38	42	42	43	30	34	34	35	23	26	27	27	46	50	50	51	42	46	45	47	36	41	41	42
	Ann3tog													32	35	35	35	24	27	27	27	16	19	19	19	41	45	42	43	36	39	38	38	30	34	33	33
	Annual5	18	21	21	22	6	7	7	8					44	47	47	45	38	42	40	40	33	36	35	36	50	54	53	50	47	50	49	47	43	46	44	44
	Annual7	28	31	30	31	18	20	21	21	9	10	11	11	48	51	51	48	42	47	47	45	39	42	40	41	52	55	55	51	50	52	53	49	47	50	51	47
	Spr5													6	7	7	7									23	25	25	25	13	14	14	14	3	3	4	4
	Sum5													11	11	12	12									32	32	32	32	19	20	20	20	7	7	8	8
	Aut5																																				
	Win5																																				
	SpSu5													42	45	45	46	32	35	35	36	23	25	26	26	52	56	54	55	46	49	48	49	40	43	43	44
	AuWi5													11	12	12	11	1	2	2	2					24	25	23	22	16	17	16	15	9	10	10	9
	SpSuAu5	12	14	14	14									45	47	45	46	37	40	39	40	30	33	33	33	51	55	51	53	47	50	48	49	43	46	44	45
Double	Annual1													5	6	7	7									17	20	20	19	10	11	12	12	3	4	4	5
	Ann3alt	13	14	14	14	1	1	1	1					39	41	40	37	34	36	35	32	28	30	29	27	46	49	45	41	41	45	42	39	38	40	39	36
	Ann3tog	1	2	2	2									28	31	29	25	22	22	22	19	16	17	16	15	38	38	36	30	33	34	32	27	27	30	28	24
	Annual5	16	16	16	14	5	6	6	6					39	39	36	32	34	34	32	28	29	30	28	25	46	45	41	36	43	43	38	33	38	38	35	30
	Annual7	23	24	22	20	14	14	14	12	5	6	5	5	43	44	37	34	39	37	34	31	35	34	32	28	48	48	40	36	45	45	39	35	42	43	37	33
	Spr5													7	8	8	8									20	20	19	18	12	12	12	11	5	5	6	6
	Sum5													13	12	12	12	1	1	1	1					26	26	23	23	17	18	17	16	10	10	10	10
	Aut5																																				
	Win5																																				
	SpSu5	3	3	3	3									38	39	37	30	29	29	27	24	21	21	20	19	48	49	45	38	41	43	40	32	36	36	35	29
	AuWi5													8	7	7	6				1					19	17	14	13	11	11	10	9	6	6	6	5
	SpSuAu5	10	11	10	10									40	40	37	31	33	34	31	27	26	28	26	22	47	46	43	37	42	42	39	33	38	39	36	30

Fig. 9. Cumulative Energy Cost Savings over 20 Years (Including Investment Costs) compared to the scenario without SWHS, in the location with PSH 4.0.



Energy cost savings (%€) PSH 5.0

	€/kWh	0.1											
	$€/m^2$	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1												
	Ann3alt	29	28	25	21	15	14	13	11	5	5	4	4
	Ann3tog	21	19	17	15	7	6	6	6				
	Annual5	39	33	28	25	27	24	21	19	17	16	14	13
	Annual7	45	36	30	27	37	30	25	23	28	24	20	19
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	20	18	15	15	5	4	4	4				
	AuWi5	2	2	2	1								
	SpSuAu5	31	28	24	21	18	16	14	13	7	6	6	6
Initial	Annual1												
	Ann3alt	4	5	6	6								
	Ann3tog												
	Annual5	18	19	19	17	2	2	2	2				
	Annual7	30	31	29	29	16	17	16	16	4	4	4	4
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	6	6	6	6								
Final	Annual1												
	Ann3alt	8	9	9	9								
	Ann3tog	4	4	4	4								
	Annual5	31	32	33	33	15	16	17	17				
	Annual7	42	43	43	44	30	32	32	32	19	20	20	21
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5												
	AuWi5												
	SpSuAu5	19	20	20	20								
Middle	Annual1												
	Ann3alt	17	18	18	18								
	Ann3tog	11	12	12	13								
	Annual5	37	38	38	38	22	24	24	24	9	9	9	10
	Annual7	47	48	47	48	36	37	37	38	26	27	27	27
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	5	5	5	5								
	AuWi5												
	SpSuAu5	26	27	27	27	7	8	8	8				
Double	Annual1												
	Ann3alt	28	30	28	27	13	14	14	13	1	1	1	1
	Ann3tog	12	13	13	12								
	Annual5	32	30	28	24	18	18	17	16	8	8	8	8
	Annual7	40	38	34	30	29	28	25	22	18	18	16	14
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	9	9	9	9								
	AuWi5												
	SpSuAu5	21	21	19	19	8	8	8	8				

	€/kWh	0.3											
	$€/m^2$	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1	20	18	17	15	8	7	6	6	1	1	1	1
	Ann3alt	56	50	44	38	49	45	41	35	44	41	37	32
	Ann3tog	49	42	37	32	43	38	33	29	38	33	28	25
	Annual5	58	47	40	35	54	44	38	33	50	41	35	31
	Annual7	61	48	39	35	59	46	37	33	54	44	35	32
	Spr5	25	22	18	18	12	11	10	10	3	3	3	2
	Sum5	30	28	22	22	18	15	14	14	8	7	7	7
	Aut5	6	6	5	5								
	Win5	8	7	6	6								
	SpSu5	54	47	39	34	47	41	34	31	40	35	30	27
	AuWi5	35	29	25	22	27	23	20	18	20	16	15	14
	SpSuAu5	56	47	39	35	51	43	36	32	45	39	33	30
Initial	Annual1												
	Ann3alt	46	48	47	47	37	39	38	39	28	30	30	31
	Ann3tog	36	38	36	34	26	27	27	25	16	18	16	17
	Annual5	50	51	48	46	44	45	42	40	37	38	36	34
	Annual7	58	57	53	50	51	52	46	46	46	46	42	41
	Spr5												
	Sum5												
	Aut5												
	Win5												
	SpSu5	39	40	37	35	27	27	26	25	15	15	14	14
	AuWi5	16	16	16	14	3	3	3	3				
	SpSuAu5	46	47	45	42	37	38	37	35	29	30	29	27
Final	Annual1												
	Ann3alt	51	53	53	54	42	44	45	45	34	36	36	36
	Ann3tog	46	48	48	49	37	39	40	40	29	31	31	31
	Annual5	59	60	59	60	52	54	54	54	47	49	49	49
	Annual7	64	64	62	63	60	60	58	59	54	56	55	55
	Spr5	6	7	7	7								
	Sum5	11	11	11	11								
	Aut5												
	Win5												
	SpSu5	49	50	50	50	38	39	39	39	27	28	28	28
	AuWi5	32	32	29	30	19	20	19	19	8	8	8	8
	SpSuAu5	54	56	56	56	47	49	49	49	40	42	42	42
Middle	Annual1												
	Ann3alt	57	60	59	60	48	51	51	51	41	43	43	43
	Ann3tog	50	53	52	52	42	45	44	44	34	36	36	36
	Annual5	63	64	62	62	57	59	57	57	52	53	52	53
	Annual7	67	69	64	65	63	64	61	62	59	60	58	58
	Spr5	14	14	14	14								
	Sum5	19	19	19	19								
	Aut5												
	Win5	1	1	1	1								
	SpSu5	53	53	53	53	43	44	43	44	33	34	33	34
	AuWi5	38	39	37	36	27	28	27	27	17	17	17	17
	SpSuAu5	58	59	59	59	51	53	52	53	44	46	46	46
Double	Annual1	19	20	19	19	5	6	6	7				
	Ann3alt	56	57	55	51	51	51	49	46	44	46	44	42
	Ann3tog	45	44	40	36	37	36	34	31	30	30	27	26
	Annual5	56	54	49	41	50	49	45	38	46	44	40	35
	Annual7	61	55	49	44	56	52	46	41	51	48	43	38
	Spr5	14	14	13	13	3	3	3	3				
	Sum5	19	19	18	18	7	7	7	7				
	Aut5												
	Win5												
	SpSu5	46	45	43	36	37	36	31	31	28	28	25	25
	AuWi5	28	26	25	23	19	19	18	16	11	11	11	10
	SpSuAu5	53	51	47	40	47	45	41	34	40	40	36	30

	€/kWh	0.5											
	$€/m^2$	500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1	33	32	29	25	25	23	22	19	16	16	15	13
	Ann3alt	61	56	48	42	58	53	46	40	54	49	44	38
	Ann3tog	57	47	41	35	52	44	38	33	48	42	36	31
	Annual5	62	53	42	37	59	50	41	36	57	46	40	35
	Annual7	64	53	41	36	63	52	40	35	61	48	39	34
	Spr5	38	33	28	25	30	27	21	21	22	20	16	16
	Sum5	46	39	33	29	36	32	28	25	28	26	21	20
	Aut5	20	17	15	14	12	10	9	8	4	4	4	4
	Win5	21	17	16	15	13	11	10	10	6	5	5	5
	SpSu5	62	53	44	38	56	49	41	36	52	46	38	34
	AuWi5	45	35	30	27	40	31	27	24	34	28	24	22
	SpSuAu5	61	50	42	38	58	48	40	36	55	46	38	34
Initial	Annual1	11	14	15	16								
	Ann3alt	54	56	55	56	49	51	50	51	44	46	45	46
	Ann3tog	47	48	46	42	40	42	40	37	34	35	34	32
	Annual5	58	59	54	52	54	54	50	48	49	50	47	45
	Annual7	65	64	61	54	61	59	54	51	57	56	52	49
	Spr5	14	14	13	14	1	1	1	1				
	Sum5	21	21	20	20	7	8	8	8				
	Aut5												
	Win5												
	SpSu5	52	52	50	47	43	44	43	39	36	37	35	33
	AuWi5	32	31	30	27	22	22	21	19	13	13	13	12
	SpSuAu5	55	55	52	50	49	50	48	45	44	45	43	41
Final	Annual1	14	16	17	17			1	1				
	Ann3alt	61	63	62	63	54	57	57	58	49	51	52	52
	Ann3tog	56	58	57	58	50	52	52	53	44	47	47	47
	Annual5	66	66	64	65	61	63	61	62	58	59	58	59
	Annual7	68	69	66	67	65	66	64	64	63	64	61	62
	Spr5	27	28	28	28	14	15	15	15	2	2	2	3
	Sum5	33	33	33	33	19	20	20	20	6	7	7	7
	Aut5	9	10	10	10								
	Win5	12	12	12	12								
	SpSu5	59	61	61	61	53	55	54	55	47	48	48	48
	AuWi5	45	45	43	40	37	37	33	34	29	29	27	27
	SpSuAu5	62	63	63	64	57	59	59	59	53	55	55	55
Middle	Annual1	21	23	23	24	8	8	9	9				
	Ann3alt	66	68	67	68	61	63	62	63	56	58	57	58
	Ann3tog	60	61	60	60	54	56	55	56	49	51	50	51
	Annual5	68	70	66	67	65	66	64	64	62	63	61	61
	Annual7	71	72	68	68	69	70	66	66	65	67	64	64
	Spr5	32	34	33	33	21	22	22	22	10	10	10	10
	Sum5	38	39	38	39	27	27	27	27	15	15	15	15
	Aut5	18	19	18	18	6	6	6	6				
	Win5	20	21	20	21	8	9	9	9				
	SpSu5	63	64	63	63	57	57	57	57	51	51	51	52
	AuWi5	51	51	47	46	43	44	41	40	36	37	34	34
	SpSuAu5	65	67	65	66	61	62	61	62	57	58	57	58
Double	Annual1	33	35	34	31	25	26	25	24	16	17	16	16
	Ann3alt	62	64	61	56	59	59	57	53	55	55	54	50
	Ann3tog	54	53	49	41	50	47	44	38	44	43	39	35
	Annual5	61	59	53	44	58	56	51	43	55	53	48	41
	Annual7	65	58	52	47	63	56	51	45	59	54	49	43
	Spr5	28	27	24	24	19	19	18	18	11	11	11	11
	Sum5	32	32	29	29	24	24	23	23	16	16	16	16
	Aut5	12	12	11	11	4	4	4	3				
	Win5	13	13	12	12	5	5	4	4				
	SpSu5	59	57	52	42	53	51	47	39	44	44	41	35
	AuWi5	39	35	32	29	33	30	28	25	26	25	23	21
	SpSuAu5	60	59	53	44	56	54	50	42	52	50	46	39

Fig. 10. Cumulative Energy Cost Savings over 20 Years (Including Investment Costs) compared to the scenario without SWHS, in the location with PSH 5.0.

values of energy cost savings obtained optimizing the system size by maximizing the "Savings/Payback" ratio. Each one presents a summary of the 2160 scenarios analyzed for each location, combining the proposed patterns with different contexts. The purpose is to provide a comprehensive view of the energy cost savings of SWHS to assist in decision-making.

A low energy price makes it impossible to achieve attractive savings, except in scenarios with high demand uniformity and medium-high radiation. With energy prices similar to those of the past year, savings increase significantly in many scenarios, including some in low radiation locations. All else being equal, higher radiation leads to substantial increases in savings, doubling in many cases from 3.0 to 5.0 PSH.

In general, the more irregular the daily demand pattern, the larger the installation required to reach the optimum size (Fig. 7). Considering all analyzed scenarios, the average number of solar collectors is 22 for the "Uniform" pattern, 55 for "Initial", 51 for "Final", 47 for "Middle", and 33 for "Double". In a standard comparison frame, where all scenarios are profitable (Annual7 and PSH 5.0), the average number of collectors is 24, 59, 51, 46, and 39 respectively for the described patterns.

The larger size of the installation in more irregular patterns leads to higher percentage savings, despite having lower efficiency and profitability. Thus, the average savings for all scenarios are 23 % for "Uniform", 26 % for "Initial", 31 % for "Final", 33 % for "Middle", and 25 % for "Double". It is essential to clarify that in more uniform patterns, savings could be increased slightly at the expense of reducing profitability and increasing investment risk.

Regarding the weekly demand pattern, an increase in the number of demand days results in higher savings achieved by the SWHS, ranging from an average of 12 % in the case of 1 day to 34 % with demand every day. A similar trend occurs in seasonality, where the average savings do not reach 10 % in patterns concentrating demand in autumn and winter, increasing to 33 % with demand from spring to autumn.

3.2.2. Reduction in energy consumption (kWh)

Focusing on the reduction of energy consumption without considering the investment costs, SWHS achieves very high percentages, up to 90 %, resulting in significantly lower annual energy bills compared to scenarios without SWHS. Consider Fig. 11 as an illustrative example, depicting the outcomes of the energy consumption reduction for the PSH 4.0 case. The accumulation of energy in the form of hot water in the tank serves as an equivalent system to batteries in photovoltaic systems, mitigating the drawbacks of irregular or seasonal patterns.

The average reduction in consumption for the set of profitable scenarios reaches 45 % with 3.0 PSH, 57 % with 4.0 PSH (Fig. 11), and 70 % with 5.0 PSH. Even in scenarios with limited financial appeal, the reduction is often substantial and could be a positive aspect in decision-making if other objectives, such as achieving industry-neutral emissions, are pursued.

Prioritizing the environmental impact of implementing SWHS, it is worth highlighting that the demand pattern strongly influences the system's emission reduction capacity. Thus, the average annual energy saved per unit of collector area for the set of scenarios analyzed is 226 kWh/m^2 in the "Annual1" pattern, 527 kWh/m^2 in "Ann3alt," 442 kWh/m^2 in "Ann3tog," 687 kWh/m^2 in "Annual5," and 878 kWh/m^2 in "Annual7." Seasonality has an even greater effect than weekly frequency, with annual averages of 236 kWh/m^2 ("Spr5"), 253 kWh/m^2 ("Sum5"), 201 kWh/m^2 ("Aut5"), 205 kWh/m^2 ("Win5"), 442 kWh/m^2 ("SpSu5"), 309 kWh/m^2 ("AuWi5"), and 567 kWh/m^2 ("SpSuAu5"). In the most favorable scenarios, with uniform pattern and high radiation, savings can reach 1400 kWh/m^2.

This significant disparity in achieved energy savings is closely related to the system's annual efficiency. Thus, the "Annual7" pattern has an average annual performance value of 53 %, while patterns like "Annual1," "Aut5," and "Win5" barely exceed 10 %. In the most favorable scenarios with uniform pattern and high radiation, performance can exceed 70 %.

Considering a country with a strong deployment of renewables in energy production, such as Spain, with an emission factor of 0.14 kg CO_2eq/kWh for electricity supply (average of energy mix in recent years), the average annual reduction in emissions achieved would range from 28 kg CO_2eq/m^2 in the least favorable pattern to 123 kg CO_2eq/m^2 in the most favorable. Considering a value of 0.29 kg CO_2eq/kWh for diesel, the range would increase to 58–255 kg CO_2eq/m^2. In the most favorable scenarios, annual reductions of 196 kg CO_2eq/m^2 for electricity and 406 kg CO_2eq/m^2 for diesel could be achieved.

Emissions reduction can be much higher in countries with greater dependence on fossil fuels in their generation systems. For example, considering a coefficient of 0.85 kg CO_2eq/kWh [26], the reduction could reach almost 2000 CO_2eq/m^2 in the most favorable scenarios.

4. Conclusions

This study have been assessed the feasibility of SWHS in the food industry. Key variables influencing their viability have been identified, paying special attention to the consumption patterns. In order to achieve this, the profitability and energy savings of SWHS in nearly 1.3 million cases have been calculated.

The result tables (optimized sizing to maximize the "Savings/payback" ratio) provide a valuable tool for industries considering the implementation of SWHS. By looking for the scenario with the most similar characteristics, it is possible to estimate the profitability and potential energy savings of the SWHS in a given industry, as well as the possible variations when changing the assumed variables.

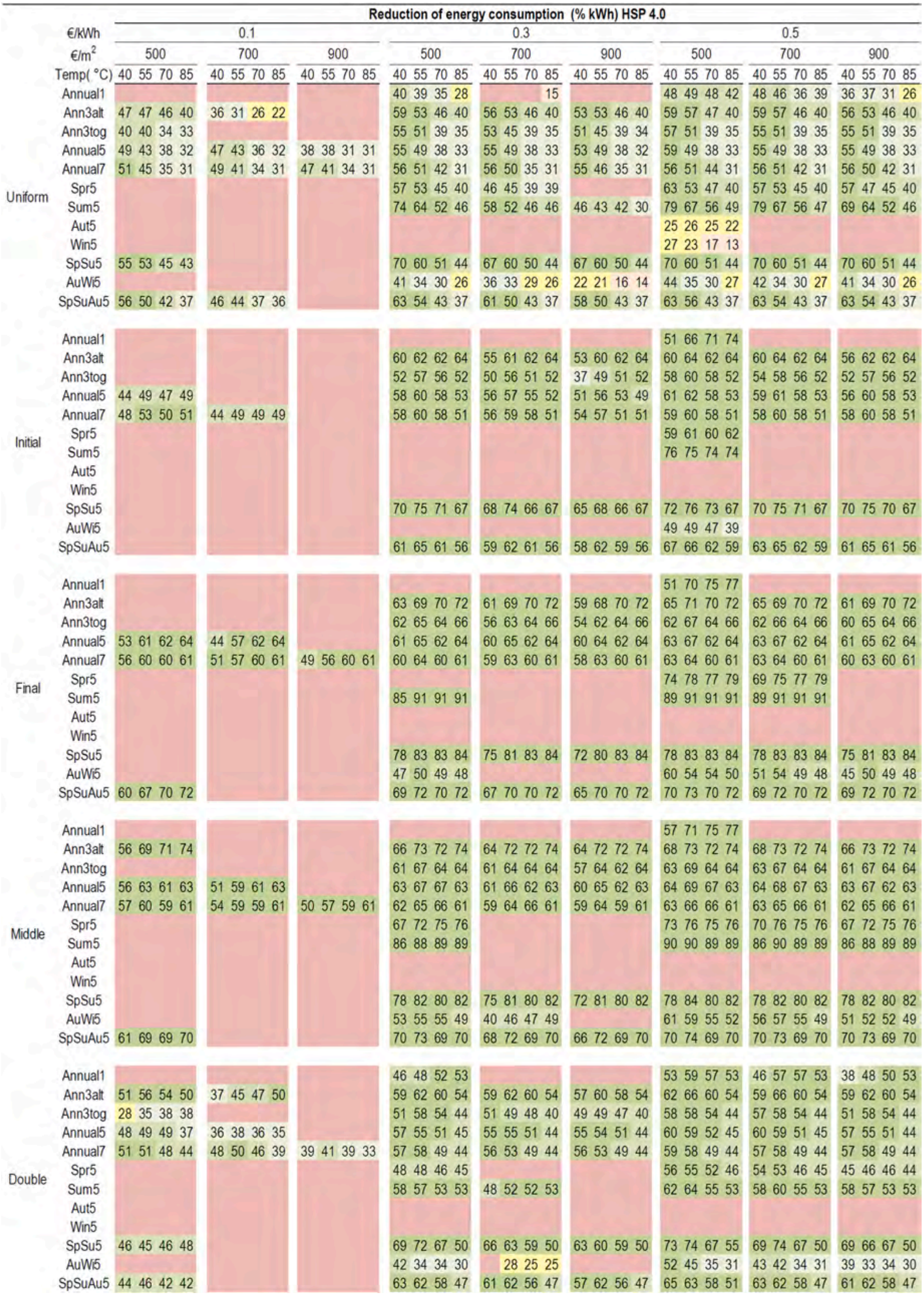
Significant findings reveal the critical role of various factors in shaping the profitability and viability of SWHS. Based on these results, some general conclusions can be drawn:

Energy Price: The energy price is a key factor in the viability and profitability of SWHS. With low prices, such as those before 2021, SWHS are only viable in very favorable scenarios (21 % of those considered), combining factors like high radiation, low investment cost, demand uniformity, and high frequency. In profitable scenarios, the achieved savings are limited (between 16 % and 31 % in the best cases). In the most favorable scenarios, the best payback ranges between 4 and 7 years, depending on the location. However, with prices close to those of recent years in most European countries (0.30 €/kWh with taxes), the number of viable scenarios increases to 61 %, with attractive paybacks in many cases (between 2 and 5 years in a large number of cases) and significant energy savings. If the record values reached in mid-2022 were to be repeated, the investment would be recovered in less than 2 years in the most favorable scenarios.

Uniformity of Daily Consumption Pattern: The viability and profitability of SWHS are penalized when demand is concentrated in a few hours. Among irregular patterns, the most unfavorable is one with a peak consumption early in the morning. The payback can double in such patterns compared to a uniform one. For example, in the most favorable scenarios at an energy price of 0.1 €/kWh, the payback increases from 4 to 8 years, with values of 5 and 6 years for intermediate patterns.

Weekly Demand Frequency: Consumption patterns with only one day per week make SWHS unviable in most scenarios. With only three non-consecutive days, values of savings and profitability close to those with five days are obtained, thanks to the energy stored in the tank. Consumption concentrated on three consecutive days slightly diminishes the viability of SWHS. Industries with consumption from Monday to Friday are less penalized compared to those with daily consumption. For example, in the most favorable scenarios at a price of 0.1 €/kWh, the payback is over 20 years for 1 day, 9–11 years for 3-day patterns, 6 years for 5 days, and 4 years for 7 days.

Seasonality of Demand: In industries strongly seasonal, such as many in the agri-food sector, the viability of SWHS is seriously compromised. In most cases, SWHS are not profitable if consumption is concentrated in a single season. However, with more than 6 months of



		Reduction of energy consumption (% kWh) HSP 4.0																																			
	€/kWh	0.1												0.3												0.5											
	€/m^2	500				700				900				500				700				900				500				700				900			
	Temp(°C)	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85	40	55	70	85
Uniform	Annual1													40	39	35	28				15					48	49	48	42	48	46	36	39	36	37	31	26
	Ann3alt	47	47	46	40	36	31	26	22					59	53	46	40	56	53	46	40	53	53	46	40	59	57	47	40	59	57	46	40	56	53	46	40
	Ann3tog	40	40	34	33									55	51	39	35	53	45	39	35	51	45	39	34	57	51	39	35	55	51	39	35	55	51	39	35
	Annual5	49	43	38	32	47	43	36	32	38	38	31	31	55	49	38	33	55	49	38	33	53	49	38	32	59	49	38	33	55	49	38	33	55	49	38	33
	Annual7	51	45	35	31	49	41	34	31	47	41	34	31	56	51	42	31	56	50	35	31	55	46	35	31	56	51	44	31	56	51	42	31	56	50	42	31
	Spr5													57	53	45	40	46	45	39	39					63	53	47	40	57	53	45	40	57	47	45	40
	Sum5													74	64	52	46	58	52	46	46	46	43	42	30	79	67	56	49	79	67	56	47	69	64	52	46
	Aut5																									25	26	25	22								
	Win5																									27	23	17	13								
	SpSu5	55	53	45	43									70	60	51	44	67	60	50	44	67	60	50	44	70	60	51	44	70	60	51	44	70	60	51	44
	AuWi5													41	34	30	26	36	33	29	26	22	21	16	14	44	35	30	27	42	34	30	27	41	34	30	26
	SpSuAu5	56	50	42	37	46	44	37	36					63	54	43	37	61	50	43	37	58	50	43	37	63	56	43	37	63	54	43	37	63	54	43	37
Initial	Annual1																									51	66	71	74								
	Ann3alt													60	62	62	64	55	61	62	64	53	60	62	64	60	64	62	64	60	64	62	64	56	62	62	64
	Ann3tog													52	57	56	52	50	56	51	52	37	49	51	52	58	60	58	52	54	58	56	52	52	57	56	52
	Annual5	44	49	47	49									58	60	58	53	56	57	55	52	51	56	53	49	61	62	58	53	59	61	58	53	56	60	58	53
	Annual7	48	53	50	51	44	49	49	49					58	60	58	51	56	59	58	51	54	57	51	51	59	60	58	51	58	60	58	51	58	60	58	51
	Spr5																									59	61	60	62								
	Sum5																									76	75	74	74								
	Aut5																																				
	Win5																																				
	SpSu5													70	75	71	67	68	74	66	67	65	68	66	67	72	76	73	67	70	75	71	67	70	75	70	67
	AuWi5																									49	49	47	39								
	SpSuAu5													61	65	61	56	59	62	61	56	58	62	59	56	67	66	62	59	63	65	62	59	61	65	61	56
Final	Annual1																									51	70	75	77								
	Ann3alt													63	69	70	72	61	69	70	72	59	68	70	72	65	71	70	72	65	69	70	72	61	69	70	72
	Ann3tog													62	65	64	66	56	63	64	66	54	62	64	66	62	67	64	66	62	66	64	66	60	65	64	66
	Annual5	53	61	62	64	44	57	62	64					61	65	62	64	60	65	62	64	60	64	62	64	63	67	62	64	63	67	62	64	61	65	62	64
	Annual7	56	60	60	61	51	57	60	61	49	56	60	61	60	64	60	61	59	63	60	61	58	63	60	61	63	64	60	61	63	64	60	61	60	63	60	61
	Spr5																									74	78	77	79	69	75	77	79				
	Sum5													85	91	91	91									89	91	91	91	89	91	91	91				
	Aut5																																				
	Win5																																				
	SpSu5													78	83	83	84	75	81	83	84	72	80	83	84	78	83	83	84	78	83	83	84	75	81	83	84
	AuWi5													47	50	49	48									60	54	54	50	51	54	49	48	45	50	49	48
	SpSuAu5	60	67	70	72									69	72	70	72	67	70	70	72	65	70	70	72	70	73	70	72	69	72	70	72	69	72	70	72
Middle	Annual1																									57	71	75	77								
	Ann3alt	56	69	71	74									66	73	72	74	64	72	72	74	64	72	72	74	68	73	72	74	68	73	72	74	66	73	72	74
	Ann3tog													61	67	64	64	61	64	64	64	57	64	62	64	63	69	64	64	63	67	64	64	61	67	64	64
	Annual5	56	63	61	63	51	59	61	63					63	67	67	63	61	66	62	63	60	65	62	63	64	69	67	63	64	68	67	63	63	67	62	63
	Annual7	57	60	59	61	54	59	59	61	50	57	59	61	62	65	66	61	59	64	66	61	59	64	59	61	63	66	66	61	63	65	66	61	62	65	66	61
	Spr5													67	72	75	76									73	76	75	76	70	76	75	76	67	72	75	76
	Sum5													86	88	89	89									90	90	89	89	86	90	89	89	86	88	89	89
	Aut5																																				
	Win5																																				
	SpSu5													78	82	80	82	75	81	80	82	72	81	80	82	78	84	80	82	78	82	80	82	78	82	80	82
	AuWi5													53	55	55	49	40	46	47	49					61	59	55	52	56	57	55	49	51	52	52	49
	SpSuAu5	61	69	69	70									70	73	69	70	68	72	69	70	66	72	69	70	70	74	69	70	70	73	69	70	70	73	69	70
Double	Annual1													46	48	52	53									53	59	57	53	46	57	57	53	38	48	50	53
	Ann3alt	51	56	54	50	37	45	47	50					59	62	60	54	59	62	60	54	57	60	58	54	62	66	60	54	59	66	60	54	59	62	60	54
	Ann3tog	28	35	38	38									51	58	54	44	51	49	48	40	49	49	47	40	58	58	54	44	57	58	54	44	51	58	54	44
	Annual5	48	49	49	37	36	38	36	35					57	55	51	45	55	55	51	44	55	54	51	44	60	59	52	45	60	59	51	45	57	55	51	44
	Annual7	51	51	48	44	48	50	46	39	39	41	39	33	57	58	49	44	56	53	49	44	56	53	49	44	59	58	49	44	57	58	49	44	57	58	49	44
	Spr5													48	48	46	45									56	55	52	46	54	53	46	45	45	46	46	44
	Sum5													58	57	53	53	48	52	52	53					62	64	55	53	58	60	55	53	58	57	53	53
	Aut5																																				
	Win5																																				
	SpSu5	46	45	46	48									69	72	67	50	66	63	59	50	63	60	59	50	73	74	67	55	69	74	67	50	69	66	67	50
	AuWi5													42	34	34	30		28	25	25					52	45	35	31	43	42	34	31	39	33	34	30
	SpSuAu5	44	46	42	42									63	62	58	47	61	62	56	47	57	62	56	47	65	63	58	51	63	62	58	47	61	62	58	47

Fig. 11. Reduction in Energy Consumption for Water Heating (%kWh) compared to the scenario without SWHS, in the location with PSH 4.0.

demand, SWHS become attractive in many scenarios with intermediate and high energy prices, where the payback is less than 5 years in a large number of cases. Nevertheless, with low energy prices, attractive returns are not achieved even in the most favorable seasonal scenarios (paybacks exceeding 10 years in the majority of cases).

Demanded Temperature: The demanded water temperature barely affects the profitability of optimized SWHS, but it does impact their size, requiring a larger investment. The collection area triples in many cases as the demanded temperature increases from 40 °C to 85 °C.

Radiation: Radiation also plays a key role in implementing a solar system. Although increased radiation leads to a decrease in payback, its most significant impact is on the achieved energy savings, doubling in many cases from 3.0 to 5.0 PSH.

Required Investment: The cost of the necessary investment can also compromise the implementation of SWHS, potentially doubling the payback when going from 500 €/m^2 to 900 €/m^2.

Global considerations: Among the factors analyzed, energy price, demand seasonality, and the weekly frequency of demand are the ones that exhibit the greatest impact on the profitability and potential savings of SWHS. Therefore, they should be scrutinized in greater detail when evaluating the implementation of an SWHS. Factors such as the uniformity of daily demand, location and investment cost are also determinants. The demand temperature primarily influences the size of the installation but has minimal impact on profitability if the SWHS design is optimized.

The demand pattern strongly influences the system's emission reduction capacity and overall efficiency. The average annual energy saved per collector area varies from values close to 200 kWh/m^2 for highly irregular patterns to nearly 900 kWh/m^2 for the most regular pattern, with peaks reaching 1400 kWh/m^2 in the most favorable scenarios (efficiency exceeding 70 %). This translates into an average emissions reduction capacity ranging between 28 and 123 kg CO$_2$eq/m^2 for electricity and 58–255 kg CO$_2$eq/m^2 for diesel, with peaks of 400 kg CO$_2$eq/m^2 in the most favorable scenarios. Considering the relevance of the food and beverage industry in global energy consumption, the development of SWHS in the sector would be a boost to achieving decarbonization and emission reduction goals.

CRediT authorship contribution statement

Rosa María Benavente: Writing – original draft, Visualization, Validation, Software, Conceptualization. **Alicia Perdigones:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Fátima Baptista:** Formal analysis, Investigation, Resources, Writing – review & editing. **José L. García:** Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing. **Fernando R. Mazarrón:** Conceptualization, Methodology, Project administration, Software, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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