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# Profitability Variations of a Solar System with an Evacuated Tube Collector According to Schedules and Frequency of Hot Water Demand

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**Abstract:** The use of solar water heating systems with evacuated tube collectors has been experiencing a rapid growth in recent years. Times when there is demand for hot water, the days of use and the volumes demanded may determine the profitability of these systems, even within the same city. Therefore, this paper characterizes the behavior of a solar system with active circulation with the objective of determining the profitability variations according to the timing and schedule of demand. Through a simplified methodology based on regression equations, calculated for each hour of the day based on data from an experimental facility, the useful energy is estimated from the time and frequency of the demand for hot water at 60 °C. The analysis of the potential profitability of the system in more than 1000 scenarios analyzed shows huge differences depending on the number of days when the water is demanded, the time when demand occurs, the irradiation and the average price of energy. In cities with high irradiation and high energy prices, the system could be profitable even in homes where it is used only on weekends. The study of profitability in a building of 10 homes shows that by applying an average European household's profile for hot water demand, levels close to full potential would be reached; for this, it is necessary to optimize the collection surface.

**Keywords:** active solar water-heating system; evacuated-tube collector; hot water; schedule of demand; profitability

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## 1. Introduction

Solar water heating (SWH) systems have been recognized as one of the most promising alternative energy systems for heating because they reduce the consumption of fossil fuels and the emission of greenhouse gases [1]. Depending on whether they require pumps or not to run, SWHs can be grouped into two basic categories, passive and active circulation systems [2]. A pump drive allows the collectors to be above or below the storage tank, allowing for greater flexibility in the location and size of the tank.

The solar collectors are the main component of any solar energy system. They gather solar radiation and transfer heat to a fluid [3]. Flat plate collectors (FPCs) and evacuated tube collectors (ETCs) are the most widely used for small-scale water heating applications [4]. Conventional FPCs were developed for use in sunny and warm climates. Their benefits, however, become unfavorable during cold, cloudy and windy days [5]. Condensation and moisture can also cause their deterioration, resulting in reduced performance and eventual system failure. ETCs have the advantage that their vacuum envelope reduces convection and conduction losses [5]; they can, therefore, perform even in cold weather when FPCs perform poorly due to heat losses [6]. ETCs also show better performance and efficiency than FPCs at high heat-transporting fluid temperatures [4–7]. Installing an ETC is expensive in some countries but it is an advanced technology at a competitive price which requires less maintenance afterwards. Therefore, for the long term, an ETC is more economical and cost effective than an FPC [8]. Two configurations are often considered depending on the absorber being in the vacuum or not, affecting performance, costs and profitability.

Recently, there has been a major expansion of the market of evacuated tube solar water heaters in China, Europe, and Japan as a result of globally growing industries for ETCs [8]. This growth has led to an increase in studies analyzing their thermal performance under specific consumption patterns, such as the recent work of Daghigh and Shafieian [9] and Ayompe and Duffy [10].

Despite its importance, few studies have examined the profitability of active SWH-ETC systems, taking into account patterns of domestic hot water demand. The findings of these studies vary greatly depending on the location, the assumed variables and the energy sources being compared. Thus, for example, Ayompe et al. [4] present year-round energy performance monitoring results of two solar water heaters (ETC and FPC), determining that under the experimental conditions in a temperate climate (Dublin), the system is not economically viable. Hazami et al. [11] analyze, through a transient systems simulation program (TRNSYS) simulation, the energetic and the economic potential of the deployment of domestic SWH systems (with FPC and with ETC) instead of using electric/gas/town gas water heaters in Tunisia, obtaining good payback periods in all cases. Hang et al. [12] evaluate the SWH systems (with FPC and ETC) for the typical U.S. residential buildings, from energetic, economic and environmental perspectives, including two types of auxiliary systems (i.e., natural gas and electricity) and three different locations; thorough simulation concludes that the ETC is not suitable for water heating systems considering the price at the time of the study. Greening and Azapagic [13] consider life cycle environmental sustainability of SWH systems (FPC and ETC) in regions with low solar irradiation, such as the UK; by simulation they reach the conclusion that solar thermal systems do not necessarily represent a more environmentally sustainable alternative to fossil fuel-based water heating. Mazarrón et al. [14] analyze how the required tank water temperature affects the useful energy that the system is capable of delivering, and consequently its profitability; they conclude that through proper sizing of the SWHs the investment in the solar system can be profitable in a location with high irradiation (Madrid), as well as with certain ranges of variation of the assumed parameters.

It seems necessary to conduct a study applying the same methodology and using current energy prices for different locations. In addition, the papers described use typical patterns of water demand, assuming its daily use, not being adapted to particular demands (houses used in weekdays, water demand after hours, etc.). Moreover, many of the studies analyzed are based solely on results of simulations, not being supported by experimental data. Energy and economic performances vary considerably depending on the weather and load conditions. Therefore, SWH systems must be designed properly to ensure that the benefits to the user are maximized [1]. Times when there is hot water demand, utilization days (weekdays, weekends, etc.) and the volumes demanded may determine the profitability of these systems, even within the same city. Therefore, this paper characterizes the behavior of an SWH with ETC, analyzing the profitability variations according to the timing and schedule of the demand for hot water at 60 °C.

## 2. Material and Methods

### *2.1. Solar Water Heating System*

To quantify the profitability of the system, it is necessary to determine the useful energy that the SWH is capable of supplying throughout the year. For this, it was designed an experimental SWH reproducing currently marketed systems of active circulation. The experimental SWH was installed on the roof of a building in Madrid (Spain).

The selected vacuum tube solar collector is model SP-S58/1800-24 of WesTech Solar (WesTech Solar Technology Wuxi Co., Ltd., Wuxi, China). This collector has 24 vacuum tubes, a net collection area of 2 m$^2$. Its features include: optical efficiency 0.691, heat loss coefficient $a_1$ 1.55 m$^2$·K, heat loss coefficient $a_2$ 0.0117 m$^2$·K, solar Keymark No. 011-7S695 R. This sensor uses a flat absorbing layer inside, so the values of transverse and longitudinal incidence angle modifier (IAM) are similar. The ETC was mounted on a south-facing metallic structure held at an angle of 41°.

The tank installed is model IAV 80/100 (737 mm × 505 mm) of the brand Thermor (Thermor España, Castelldefels, Spain) with an exchange system through coil (0.53 m$^2$ exchange surface and interior volume of 3.5 L exchanger) and 80 L capacity. It presents high density thermal insulation and glazed stainless steel container. The copper pipes have an inner diameter of 20 mm and a thickness of 1 mm, and are coated with 13 mm-thick insulation material. The pump used was the Wilo-Star-ST 15/6 ECO-3 (Wilo SE., Dortmund, Germany) submerged rotor model (4.5 m head, 0.2 m$^3$·h$^{-1}$). Water has been used as a heat transfer fluid.

The control subsystem installed consists of two regulatory subunits: a controller Allegro 453 (Sonder Regulación, S.A, Rubí, Spain), responsible for controlling the operation of the pump of the collector circuit (original controller of the system) and an automat SIEMENS PLC logo that controls the emptying of the tank (added to carry out the experiment, automatizing the water withdraw). Control probes (SC1–SC3) are of type PTC (Positive Temperature Coefficient) 1000, temperature range −50 °C–150 °C and accuracy of ±0.15 °C at 0 °C (Figure 1).

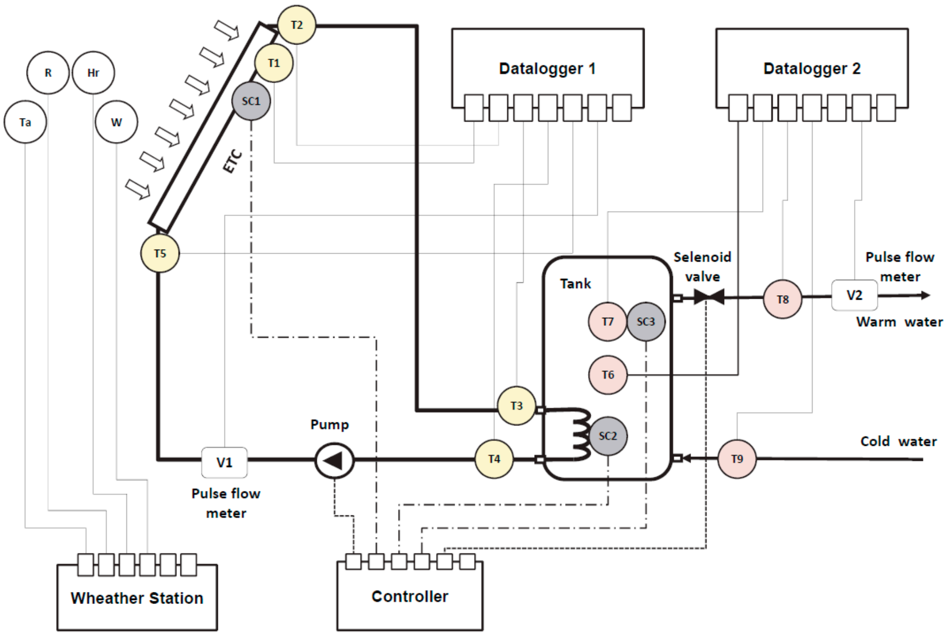

**Figure 1.** Main components of the active solar water heating (SWH) system. ETC: evacuated tube collector.

The water pump in the primary circuit was configured following the recommendations of the ETC manufacturer in order to reproduce the normal operating conditions. It is intended to determine the maximum production potential of the system. For this, the controller 2 opens the emptying electrovalve when it detects the sensor SC3—near the exit at the top of the tank—registers a temperature of 61 °C and closes the electrical valve when the sensor registers 59 °C. Every day the controller 2 activates the complete emptying of the tank to start at the temperature of the supply network.

Sensors and data loggers have been placed at strategic points in the installation to obtain and store detailed information on the operation of the system. To monitor the temperature, 10 probes (T1–T10) of PTC 100 type were used, with temperatures ranging from −50 °C to 150 °C and accuracy of ±0.15 °C at 0 °C. For flow monitoring, two mechanical flow meters with digital readout were installed: one near the inlet of the collector, which measures the flow of the primary circuit, and one on the hot water outlet of the tank, which records the volume of hot water provided. The flow meter has a mechanic contactor, recording one pulse per liter.

The meteorological parameters were recorded using a Micro Weather Station HOBO Micro-HWS (Onset Computer Corporation, Bourne, MA, USA). Solar irradiance is measured using a pyranometer HOBO Weather Station Smart Silicon Pyranometer Sensor (Onset Computer Corporation, Bourne, MA, USA) for Total Solar radiation (R), —measuring a range between 0 and 1280 $W{\cdot}m^{-2}$, with an accuracy of ±10 $W{\cdot}m^{-2}$ or ±5%. This sensor measures the radiation between 300 and 1100 nm. The pyranometer was installed with the same angle of inclination than the ETC.

In addition, other parameters were monitored, such as ambient temperature ($T_a$), wind velocity ($W$) and relative humidity ($H_r$). The ambient temperature and relative humidity were monitored by sensors housed in a plastic capsule, with precision of ±0.2 °C and range from 0 °C to 50 °C for temperature and ±2.5% and range from 5% to 95% of relative humidity. To monitor the wind speed a cup anemometer has been used with measuring range of 0–45 $m{\cdot}s^{-1}$, resolution of 0.38 $m{\cdot}s^{-1}$ and maximum deviation ±1.1 $m{\cdot}s^{-1}$.

The monitoring was carried out over one year, recording measures with an interval of 1 min, from 1 July 2014 to 30 June 2015. The monitoring was carried out each 5 days, as the remaining days the installation was configured to obtain data for another experiment, at different temperatures than those required for hot water in homes. During this period, the average daily temperature ranged between 30.9 °C and 1.3 °C, with an average annual value of 16.3 ± 8.3 °C; the daily average relative humidity between 89% and 24%, with an average of 55% ± 17%; the wind speed reached a maximum (daily average) value of 1.4 $m{\cdot}s^{-1}$ with an annual average of 0.5 ± 0.4 $m{\cdot}s^{-1}$.

### 2.2. Useful Energy

The multiple sensors installed have allowed to carry out a thorough characterization of the system performance. The calculation of variables such as energy collected by the ETC, the supply pipe losses or the system efficiency are essential to understand the operation of the system and check the validity of the data. However, given that the objective is to calculate profitability, attention will focus on the useful energy. As in other studies [14], the energy delivered to the tank is considered useful energy of the SWH, as the complementary delivery system would harness this energy, increasing the temperature of the water if 60 °C are not reached:

$$Q_d = \dot{m}C_p(T3 - T4)/A_c \tag{1}$$

where $Q_d$ is the useful heat delivered to the tank ($W{\cdot}m^{-2}$), $\dot{m}$ is the mass flow rate of the heat transfer fluid ($kg{\cdot}s^{-1}$), $C_p$ is the specific heat capacity of the collector heat-transfer fluid ($J{\cdot}kg^{-1}{\cdot}{}^{\circ}C^{-1}$), $T3$ is the temperature of the heat-transfer fluid on entering the tank's heat exchanger (°C), $T4$ is the temperature of the heat-transfer fluid on leaving the tank's heat exchanger (°C) and $A_c$ is the useful area of the ETC ($m^2$).

The useful energy has been calculated on an hourly basis, which will determine a more realistic profitability depending on the time at which the hot water is demanded. During the monitoring period $T3$ daily average values fluctuated between 48.5 °C and 15.6 °C, being the annual average of 39.2 ± 8.0 °C; $T4$ between 45.4 °C and 15.1 °C, with an annual average of 36.8 ± 7.2 °C; daily solar radiation between 8249 $Wh{\cdot}m^{-2}$ and 450 $Wh{\cdot}m^{-2}$, with an annual average of 5808 ± 2145 $Wh{\cdot}m^{-2}$.

It was carried out linear regression analysis relating the useful energy accumulated throughout the day with solar irradiation in the plane of the ETC. The resulting equations, type $Y = \beta_0 + \beta_1 X$, allow us to estimate the annual useful energy in different locations, from daily irradiation values in the working plane of the collector. Heat loss due to low temperatures or wind is minimized with ETCs, reducing possible errors in the estimate. Following this methodology, we estimated the annual useful energy that the SWH is capable of providing in 6 of the most populated cities in Europe: Berlin, Bucharest, London, Madrid, Paris and Rome.

To determine the solar irradiation incident on the plane of the collector simulations have been performed in EnergyPlus (U.S. Department of Energy's Building Technologies Office, Washington, DC, USA). To maximize the annual energy captured, the collectors have been put facing south, using as tilt of the collector the latitude of the place, in particular, 52°, 45°, 51°, 41°, 49° and 42° for Berlin, Bucharest, London, Madrid, Paris and Rome, respectively. The simulation has consisted of placing a flat surface equivalent to the collector with the corresponding inclination to the latitude of the place, running an annual simulation, obtaining values of incident radiation on the surface for each day of the year.

### *2.3. Profitability Analysis*

The profitability of the system has been evaluated assuming that the SWH acts as a complementary system to the existing traditional supply. Two alternatives to traditional supply were analyzed, a diesel boiler with an efficiency of 96% and calorific value of diesel of 10 $\text{kWh}\cdot\text{L}^{-1}$, and an electric boiler. At present (2015), the average cost ($€\cdot\text{kWh}^{-1}$) of natural gas in the EU (0.0685 $€\cdot\text{kWh}^{-1}$, according to Eurostat, natural gas prices for household consumers—bi-annual data from 2007 onwards, including all taxes and levies) is very similar to diesel (0.07014 $€\cdot\text{kWh}^{-1}$, according to Cores, corporation of strategic reserves of petroleum products), so to not overly extend the length of the article a third alternative supply will not be analyzed. The cost of the boiler has not been taken into account, considering that it will always be necessary because of the limited production capacity of SWHs in winter.

The system's profitability has been quantified taking into account the variations in cash flow originating from the initial investment necessary for SWH versus traditional supply. These cash flows will allow quantifying the profitability of the SWH through the net present value (NPV), NPV/Investment ratio, internal rate of return (IRR) and discounted payback period. To calculate profitability indicators the following parameters have been assumed:

- Investment: in recent years the price of SWHs has undergone a remarkable reduction, so nowadays (Summer 2016) units equivalent to that one used are available for approximately 700 $€\cdot\text{m}^{-2}$, including assembly.
- Electricity prices: for each country the average price of electricity for domestic Consumers of the last 5 years (2011–2015) has-been used, all taxes and Levies included (according to Eurostat, Electricity prices for domestic Consumers—bi-annual data from 2007 onwards). Specifically, 0.280, 0.121, 0.183, 0.222, 0.153, 0.228 $€\cdot\text{kWh}^{-1}$ for Berlin, Bucharest, London, Madrid, Paris and Rome, respectively.
- Diesel prices: for each country the average selling price to the public of heating diesel of the last 5 years (2011–2015) has been used (according to Cores, corporation of strategic reserves of petroleum products). Specifically, 0.822, 1.130, 0.782, 0.851, 0.873, 1.362 $€\cdot\text{L}^{-1}$ for Berlin, Bucharest, London, Madrid, Paris and Rome, respectively.
- Discount rate: a discount rate of 4%, average rate of a Spanish 10-Year government bond of the last five years (2011–2015) has been used.
- The useful life of the facility has been set at 20 years.

The frequency and times at which the hot domestic water is demanded is highly variable, being difficult to establish conclusions on the profitability of the SWH. For example, profitability will not be the same in a habitual residence with demand 7 days a week and in a residence used only for business days. Therefore, it has been conducted a double approach, analyzing the potential profitability of the SWH in a wide casuistic and the profitability assuming a typical pattern of demand in houses.

### 2.3.1. Potential Profitability of the Solar Water Heating System

It is intended to determine the maximum performance of the system depending on the time and weekly frequency of the hot water demand. This information will allow us to estimate the profitability for demands of other houses than those used in this work, depending on the time at which the main demand occurs. To do so, a multiple demand patterns will be analyzed, determining the viability of the system at intervals of 1 h (from 8:00 to 20:59) and assuming different days of demand per week (from 1 day to 7 days per week). Thus, for each city 182 different scenarios (91 for diesel boiler and 91 for electric boiler) will be studied.

To determine the full potential of the SWH it is assumed that all the useful energy is harnessed. This scenario would correspond to the one of an installation designed to provide, without storing an excess energy, the required hot water in the days of higher system performance in summer.

The cash flows for each year are calculated as differences in payments before investment ($P_b$, generated by the traditional supply) and payments after the investment ($P_a$, generated by the SWH). The product of the annual energy consumption of the pump (kWh·m$^{-2}$) for the price of electricity will be used as $P_a$. The quantity of diesel needed to provide the same useful energy multiplied by the price of the diesel will be defined as $P_b$ for the diesel boiler; for electric boiler, the payment before investment has been calculated as the product of the electric annual energy consumption (in order to provide the same useful energy extracted by the SWH) for the price of electricity.

The residual energy not used at the end of the day and that would be stored in the tank has not been taken into account in most of the analyses performed, since the night losses in the tank can be very high and the casuistry would expand considerably. However, it has added an example of profitability analysis carried out for a specific location, assuming different percentages of residual energy (0%, 25%, 50% and 75%) available the next day at the time of demand.

### 2.3.2. Profitability in a Building of 10 Homes Assuming a Typical Demand Pattern

To carry out the analysis we will assume a hot water demand profile based on hot water use of the average European household, in particular, the EU reference tapping cycle number 3, used by Ayompe and Duffy in previous works [4,10,15,16]. This pattern features 24 draw-offs with the energy, includes 2 baths and 1 shower (Figure 2). Therefore, the total demand of the building will be the result of multiplying by 10 the typical pattern described, seven days per week.

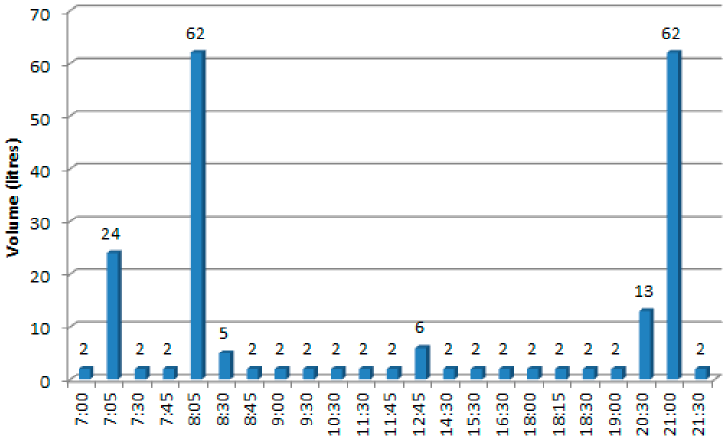

**Figure 2.** Hot water (60 °C) demand profile based on hot water use of the average European household.

The surface of the collectors necessary to minimize the total energy expenditure (SWH and traditional supply) over the life of the solar installation has been optimized. The percentage of demand covered by SWH for each day of the year, depending on the sunlight, has been calculated; the remaining energy to reach the demand is supplied by the traditional boiler. On days when the solar system can supply more than the demand, only the demand is counted; the extra energy it could supply is discarded. For this we have taken into account the energy that the solar system is able to supply every hour depending on irradiance (and that has not been previously supplied), accounting for the remaining energy as supplied by conventional power source.

In this case, the cash flows for each year are calculated as differences in $P_b$ (generated exclusively by the traditional supply) and $P_a$ (generated by the SWH and the traditional supply).

To calculate the energy needed for water at 60 °C, it is necessary to know the temperature of the supply network throughout the year. Needless to say, it is impossible to establish a water temperature of the supply network that fits all cases, even within the same city or the same neighborhood, because it depends on the ratio of demand, the situation and isolation of pipes, the depth to which the supply pipes supplying the building are buried, etc. An estimate could be to take soil temperature at a particular depth, taking into account the supply network of the city. Therefore, the temperature of the supply network of the different locations (except Madrid) has been estimated as the ground temperature to 2 m depth—available in the climatological files (file extension *epw) of EnergyPlus (https://energyplus.net/weather).

## 3. Results and Discussions

### 3.1. Useful Energy Provided by the Solar Water Heating

The useful energy transferred to the tank increases as the hours pass. It can be assumed that the accumulated useful energy increases linearly with irradiation, which is most evident later in the day (Figure 3). This very stable behavior throughout the year confirms the good performance of SWH with ETC during cold, cloudy and windy days.

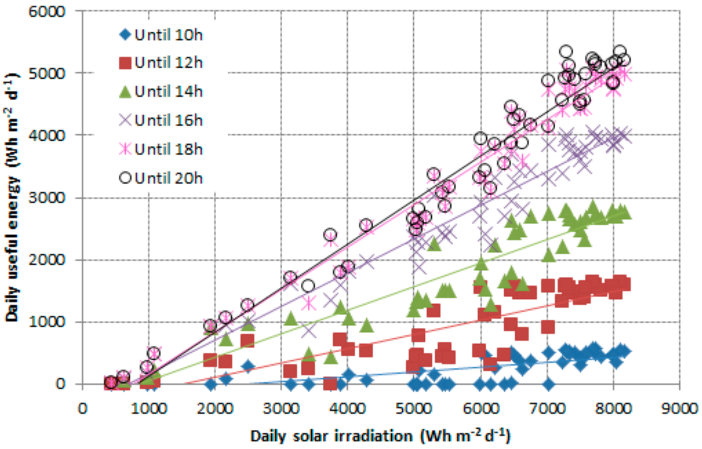

**Figure 3.** Daily energy delivered to the tank with irradiation, for different times of day.

The regression adjustment conducted confirms the strong linear relationship between irradiation and useful energy accumulated over the hours. This simplified model based on experimental data allows us to roughly estimate the useful energy available at any time of day, and thus carry out further analysis of profitability in hundreds of scenarios. The typical error of the model is less than 310 $Wh{\cdot}m^{-2}$ at all hours (6% of maximum daily useful energy), acceptable error considering the purpose of the study (Table 1). The coefficient of determination is high in the corresponding adjustments for the central and final hours of the day, reaching maximum values of 0.97; the value decreases in the early hours of the day, due to so little useful energy collected and the variation of the sunrise, but it is associated with small errors.

**Table 1.** Main parameters of regression adjustment.

| Time Interval | $R^2$ | Error ($\mathrm{Wh{\cdot}m^{-2}{\cdot}d^{-1}}$) | Error (% max) | $\beta_1$ | $\beta_0$ |
|---|---|---|---|---|---|
| Until 9:00 | 0.37 | 49.03 | 1% | 0.02 | −50.83 |
| Until 10:00 | 0.50 | 158.68 | 3% | 0.08 | −186.02 |
| Until 11:00 | 0.57 | 290.59 | 5% | 0.16 | −344.94 |
| Until 12:00 | 0.72 | 305.30 | 6% | 0.23 | −361.03 |
| Until 13:00 | 0.82 | 309.84 | 6% | 0.31 | −378.99 |
| Until 14:00 | 0.87 | 309.32 | 6% | 0.38 | −334.84 |
| Until 15:00 | 0.92 | 294.82 | 6% | 0.46 | −354.72 |
| Until 16:00 | 0.95 | 273.30 | 5% | 0.54 | −368.94 |
| Until 17:00 | 0.96 | 254.65 | 5% | 0.62 | −429.95 |
| Until 18:00 | 0.97 | 274.97 | 5% | 0.69 | −536.17 |
| Until 19:00 | 0.96 | 300.05 | 6% | 0.71 | −589.30 |
| Until 20:00 | 0.96 | 305.32 | 6% | 0.71 | −593.93 |
| Until 21:00 | 0.96 | 305.32 | 6% | 0.71 | −593.93 |

From the regression lines calculated, we estimated the annual useful energy that the SWH is able to provide depending on the days of use, in 6 of the most populated cities in Europe (Figure 4). To this end solar radiation data have been used in the plane of the collector, simulated by EnergyPlus by an area equivalent to the collector inclined according to the latitude of the place (the simulation has only been used to provide data of incident irradiation in the plane of the collector). The times of the equations refer to the facility in Madrid, where sunrise varies between 6:45 a.m. in summer and 8:30 a.m. in winter.

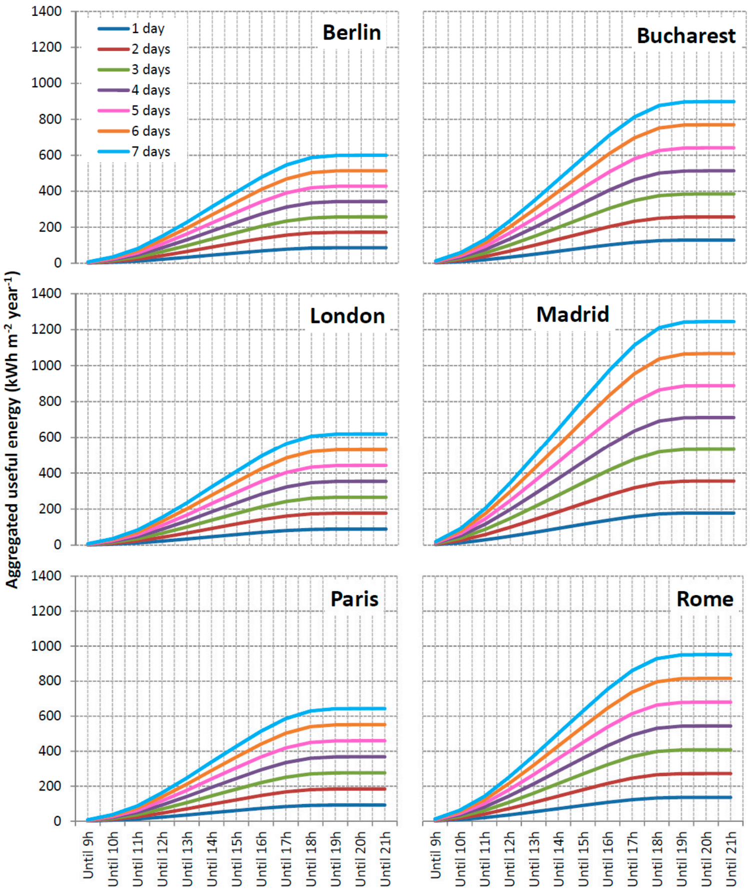

**Figure 4.** Annual energy delivered to the tank, depending on time of day and the number of days per week that the SWH is used.

### 3.2. Potential Profitability of Solar Water Heating

Based on the annual useful energy that the SWH is capable of supplying at any time of the day (obtained in the previous section), the SWH profitability for different locations has been determined. In the methodology section, we detail the procedure used. The 1092 scenarios analyzed show huge variations in performance depending on the number of days in which the water is demanded, the time at which the main demand occurs, irradiation and energy prices (Figures 5 and 6).

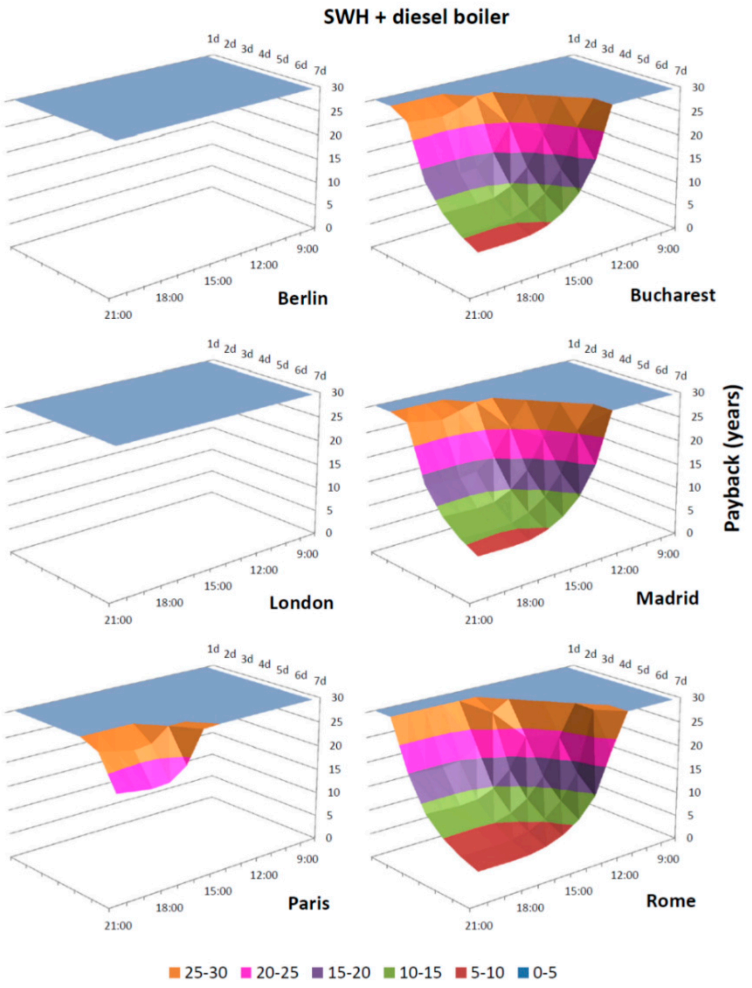

**Figure 5.** SWH profitability (updated payback) in a facility with a diesel boiler, depending on the time and number of days per week that the hot water is demanded.

In the case of a system with diesel boiler, the combination of low irradiation with relatively low diesel prices make the system not profitable in cities like Berlin, London or Paris; even in the most favorable demand scenarios, 7 days in late afternoon (Figure 5). By contrast, in cities like Bucharest, Madrid and Rome, where higher irradiation and a higher price of heating diesel coincide, the SWH begins to be profitable from the third or fourth day of use—whenever it is demanded at last time in the afternoon—and from noon if demand is 7 days a week. The updated payback can reach values below 9 years in Bucharest and Madrid and less than 7 years in Rome; the NPV/Investment ratio reaches values of 0.96 in Bucharest, 0.86 in Madrid and 1.34 in Rome; IRR presents the maximum values of 13%, 12% and 16% in Bucharest, Madrid and Rome respectively.

When it comes to an installation with electric boiler, SWH has good profitability in a great number of scenarios in all locations (Figure 6). This is due to the high price of electricity for domestic consumers, meaning a greater cost than heating diesel. In every city less than 10 years paybacks can be obtained when demand is concentrated in the afternoon every day of the week, reaching values of 3 years in Madrid and 4 years in Rome. In Paris the SWH begins to be profitable from the fifth day of use per week due to lower electricity prices; in cities like Bucharest or London from the fourth day; in Berlin in 3 days; in Madrid and Rome the system could be profitable using it only 2 days per week. The NPV/investment ratio reaches maximum values of 1.91, 0.96, 0.97, 4.11, 0.72 and 2.84 for Berlin, Bucharest, London, Madrid, Paris and Rome respectively.

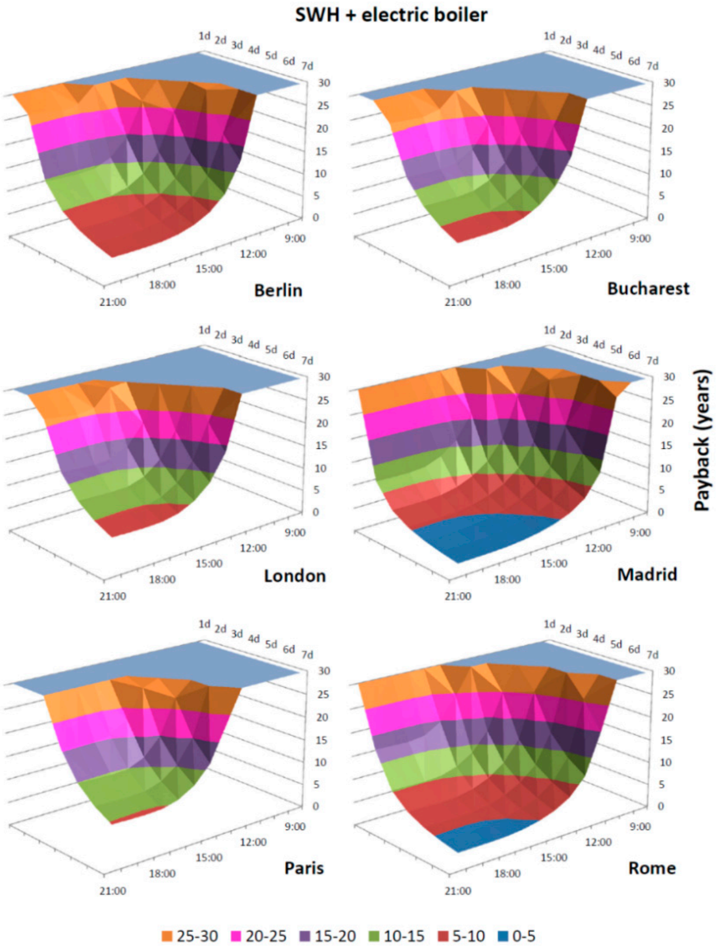

**Figure 6.** SWH profitability (updated payback) in a facility with an electric boiler, depending on the time and number of days per week that the hot water is demanded

The scenarios presented do not take into account the residual energy that has not been used and that would be stored in the tank in the late afternoon, as the night losses in the tank can be highly variable and casuistry would expand considerably. The scenarios in which demand occurs in the afternoon would barely be affected, since they consume almost all the energy collected during the day. Profitability in cases where demand occurs only during the early morning hours would increase if a well-insulated tank was provided as to minimize the energy losses at nighttime. One example is the profitability analysis carried out for the location of Madrid with diesel boiler, assuming different percentages of residual energy available the next day at the time of demand (Figure 7). As the percentage of available residual energy increases, the influence of the hour of demand decreases, tending to equal the value of the afternoon. The most favorable scenario would be a tank which does not lose any energy or very little; in this case, profitability would increase to values equivalent to those cases with consumption in the afternoon. It is necessary to clarify that the scenarios of exclusive consumption in the morning are not common in cities, because the typical pattern of a building will present consumption both morning and evening, using most of the stored energy.

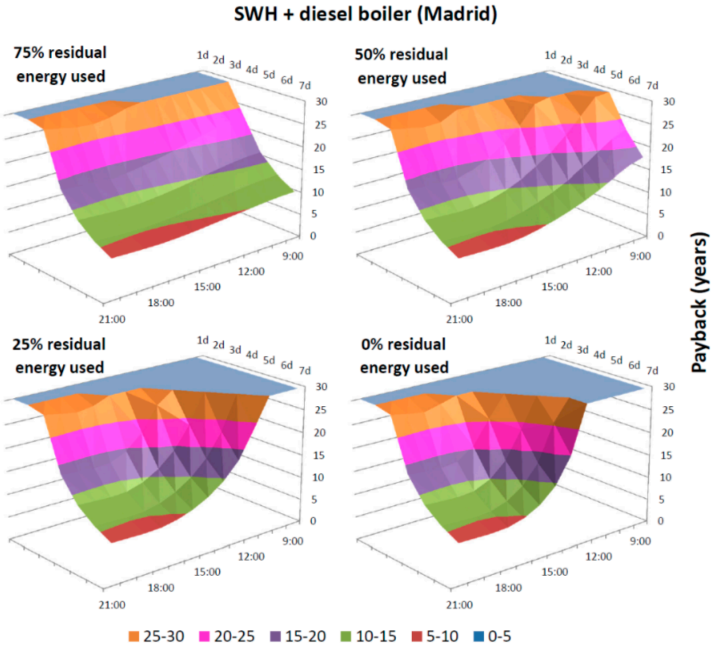

**Figure 7.** SWH profitability (updated payback) in a facility with diesel boiler, for different scenarios of residual energy available the next day.

### *3.3. Profitability in a Building of 10 Homes*

An end user should determine the economically optimal solar collector area of an SWH according to the hot-water-consumption pattern [17]. The profitability of the SWH can be seriously compromised with an inappropriate choice of the collection surface, as the energy costs over the useful life tend to skyrocket (Figure 8). Therefore, in all cases, the optimum number of solar collectors that minimizes the energy consumption of the installation over its useful life has been determined.

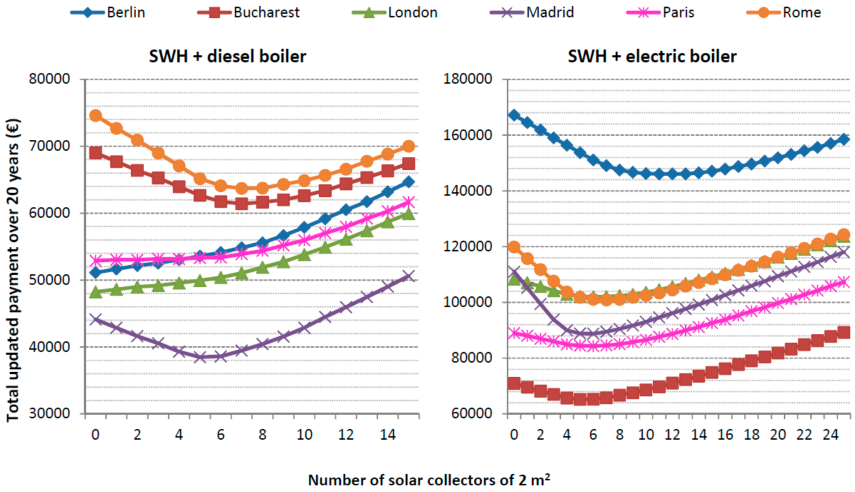

**Figure 8.** Total energy cost (including installation) over 20 years in the building of 10 homes, depending on the number of solar collectors installed and the type of conventional supply (diesel boiler and electric boiler).

In most scenarios the choice of the optimal number of collectors leads to significant savings over exclusive conventional supply (with 0 collectors). In cities where the combined SWH with a diesel boiler is not profitable, the installation of a small number of collectors would only increase slightly the total energy expenditure, so installing them could be justified on the basis of other criteria, such as environmental ones. The differences between some cities and others are marked by irradiation (a minimum value is necessary to be profitable), but also by the price of conventional energy.

Except in the three scenarios where it is not profitable, the SWH provides between 27% and 32% of annual consumption in the case of installation with diesel boiler and between 17% and 37% in the case of installation with electric boiler. Given that 50% of the demand occurs early in the morning when the solar system just captured the energy, the SWH provides an important part of the energy consumption of the rest of the day. Thus, much of the energy demand in small volumes of water in the middle of the day is covered by the SWH; the percentage of the high demand for hot water at the end of the day covering the SWH varies greatly from one city to another, ranging between 24% and 64% (Figure 9).

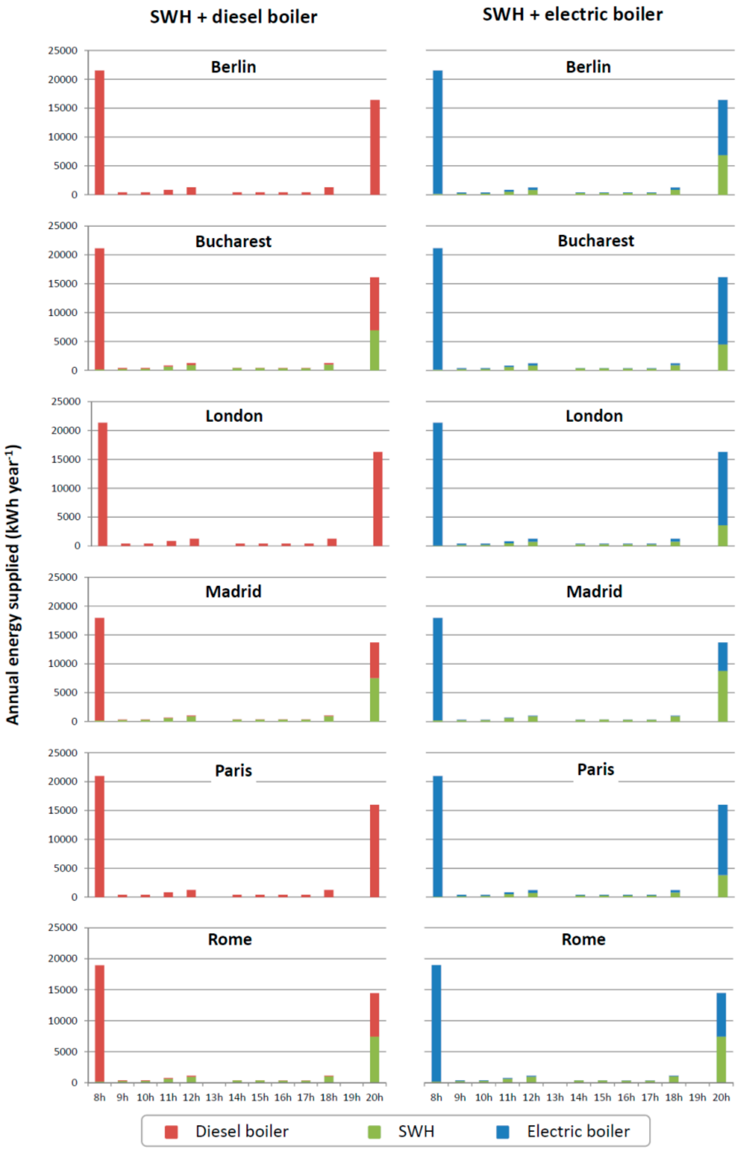

**Figure 9.** Annual energy provided by a different supply source in each of the time intervals.

Once the investment is made—between 7000 € and 15,400 €—the energy supplied by the SWH represents annual savings ranging between 930 € and 2833 € depending on the location (Table 2). Except in the 3 cases discussed previously, investment in SWH would present a good profitability, with updated paybacks of less than 10 years in all cases, and could reach values of less than four years. The IRR exceeds 10% in all cases profitable, reaching extremely high values of profitability in the most favorable cases. The NPV/investment ratio exceeds unity in many of the scenarios studied.

**Table 2.** Profitability indicators of the installation in the building of 10 homes. NPV: net present value; and IRR: internal rate of return.

| Supply | Indicator | Unit | Berlin | Bucharest | London | Madrid | Paris | Rome |
|---|---|---|---|---|---|---|---|---|
| SWH + Diesel boiler | Irradiation | $kWh\cdot m^{-2}\cdot year^{-1}$ | 1115 | 1565 | 1152 | 2003 | 1187 | 1641 |
| | Collectors (2 $m^2$) | No. | 0 | 7 | 0 | 5 | 0 | 7 |
| | Investment | € | 0 | 9800 | 0 | 7000 | 0 | 9800 |
| | Boiler supply | $kWh\cdot year^{-1}$ | 43,927 | 31,377 | 43,574 | 26,486 | 42,791 | 26,486 |
| | SWH supply | $kWh\cdot year^{-1}$ | 0 | 11764 | 0 | 12108 | 0 | 12202 |
| | Annual saving | $€\cdot year^{-1}$ | 0 | 1281 | 0 | 930 | 0 | 1523 |
| | NPV | € | - | 7605 | - | 5643 | - | 10,900 |
| | NPV/investment | €/€ | - | 0.78 | - | 0.81 | - | 1.11 |
| | IRR | % | - | 11.6 | - | 11.9 | - | 14.5 |
| | Payback | Years | - | 9.3 | - | 9.1 | - | 7.6 |
| SWH + Electric boiler | Collectors (2 $m^2$) | No. | 11 | 5 | 6 | 6 | 6 | 7 |
| | Investment | € | 15,400 | 7000 | 8400 | 8400 | 8400 | 9800 |
| | Boiler supply | $kWh\cdot year^{-1}$ | 32,898 | 34,128 | 36,173 | 23,158 | 35,096 | 26,486 |
| | SWH supply | $kWh\cdot year^{-1}$ | 11,029 | 9013 | 7401 | 13,462 | 7695 | 12,202 |
| | Annual saving | $€\cdot year^{-1}$ | 2685 | 1013 | 1211 | 2833 | 1060 | 2574 |
| | NPV | € | 21,092 | 6761 | 8062 | 30,102 | 6010 | 25,182 |
| | NPV/investment | €/€ | 1.37 | 0.97 | 0.96 | 3.58 | 0.72 | 2.57 |
| | IRR | % | 16.6 | 13.3 | 13.% | 33.6 | 11.1 | 26.0 |
| | Payback | Years | 6.6 | 8.3 | 8.3 | 3.2 | 9.7 | 4.2 |

## 4. Conclusions

This article analyzes the influence of the characteristics of water demand on the profitability of an SWH with ETC and active circulation. Specifically, it analyzes how that demand influences the time of day in which the water is demanded and the number of days per week it is demanded. Secondarily, it analyzes the influence of differences in energy prices of conventional sources of supply (electricity and diesel) and variations in profitability in different locations in Europe.

For that purpose, a simplified methodology based on regression equations (standard error of the model is less than 310 $Wh\cdot m^{-2}$ in all equations) calculated for each hour of the day from data of an experimental facility has been applied. This methodology allows us to estimate the useful energy available at different times of the day in hundreds of scenarios, and from that, the profitability of the system.

The analysis of the system's potential profitability in more than 1000 scenarios (6 cities; in each, 91 scenarios assuming a diesel boiler and 91 with an electric boiler) shows huge differences depending on the number of days that the water is demanded, the time when that demand occurs, the irradiation and the average price of energy for the last five years of each city. As the percentage of available residual energy in the tank increases, the influence of the hour of demand decreases.

In the case of a system with diesel boiler, in cities where high irradiation and high price of heating diesel coincide, the SWH begins to be profitable from the third or fourth day of use, as long as it is demanded in the last hour in the afternoon; it would be feasible for houses used exclusively on working days or with frequent absences for business trips. It would also be profitable after noon if there were demand seven days a week.

In scenarios of maximum profitability, paybacks between seven and nine years are achieved, with IRR above 12%. In cities where low irradiation is combined with a relatively low current price of diesel, SWH would not be profitable, even with demand at last time of the day, seven days a week.

When it comes to an installation with an electric boiler, SWH has good profitability in a great number of scenarios in all locations analyzed, due to the high price of electricity for domestic consumers in EU. In every city paybacks of less than 10 years can be achieved when demand is concentrated in the afternoon every day of the week. In cities such as Madrid and Rome, values of three or four years can be reached; the system could be profitable even using it only two days per week, it remains viable for weekend residences if a significant demand for water occurs during the afternoon.

The study of profitability in a building of 10 homes shows that by applying an average European household's profile for hot water demand, levels close to full potential would be reached. This requires optimizing the design of the number of collectors, as the profitability of the SWH can be seriously compromised with an inappropriate choice of the collection surface. The SWH covers much of the energy demand in small volumes of water in the middle of the day, and between 24% and 64% of the high demand at the end of the day; demand early in the morning has to be covered mostly by the conventional supply system.

The study was carried out using current data of energy prices. If the price of energy increases in the coming years or the price of the equipment decreases, the profitability of these systems would increase.

The results of the study may be useful to increase the implementation of SWH system, allowing profitability to be estimated according to the specific demand and location of buildings, contributing to the urban generation of renewable energy in order to achieve more sustainable cities.

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## Nomenclature

| | |
|---|---|
| $A_c$ | Useful area of the ETC ($m^2$) |
| $C_p$ | Specific heat capacity of the collector heat-transfer fluid ($J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$) |
| ETC | Evacuated tube collector |
| FPC | Flat plate collector |
| IRR | Internal rate of return |
| $\dot{m}$ | Mass flow rate of the heat transfer fluid ($kg \cdot s^{-1}$) |
| NPV | Net present value (€) |
| $P_a$ | Payments after the investment |
| $P_b$ | Payments before investment |
| $Q_d$ | Useful heat delivered to the tank ($W \cdot m^{-2}$) |
| R | Solar radiation ($W \cdot m^{-2}$) |
| T1–T10 | Temperature probes of the monitoring subsystem |
| SC1–SC3 | Temperature probes of the control subsystem |
| SWH | Solar water heating system |

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