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# Application of a Costing Methodology to Estimate Capital Costs of Solar Thermal Systems in Residential Portuguese Context

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**ABSTRACT**

The concerns regarding the environmental damage require changes not only on how the energy is consumed but also how it is produced. The close relationship between energy use and the economic growth exposes the need for continuous monitoring of energy consumption, which cannot be achieved without assessing capital and operational costs from its conversion to end-use. Solar thermal systems offer few advantages over other renewable resources to meet the energy demand in the small-scale building sector. Solar-thermal technologies can play a leading role in meeting the decarbonisation targets set in Europe. The reports from the International Energy Agency (IEA) show that solar heating has the potential to cover more than 16% of the low-temperature heat use in the energy mix. In Europe, this share might translate into 45% growth of the installed solar thermal capacity by 2020, setting a challenging target of 1.3 m$^2$ in terms of installed area of solar collectors by 2050. The main objective of the present work is to define a costing methodology able to estimate the capital cost of solar-thermal systems according to the system size and energy requirements of a specific residential building. The costing methodology consists of the derivation of a cost expression for each component by integrating thermodynamic and cost coefficients, adjusted for this kind of technology, and also taking into account real market data. The model was validated for a reference dwelling in Lisbon, with an occupation of 4 people with an estimated energy need of 2 037 kWh/year in terms of DHW. Results of the reference scenario show that is required at least 4 m$^2$ of solar collector and the system cost ranges from 703.2 €/m$^2$ to 763.2 €/m$^2$, depending on the acceptable storage tank capacity. These values represent investments costs between 2 812.6 € and 3 052.8 €, which are in agreement with the data from the solar systems market since the prices of active systems start at 2 500 € for single dwelling buildings. In conclusion, the use of solar thermal systems enables the minimization of energy costs and, in some cases, the systems are capable of covering more than 40% of the total building energy load.

***Keywords:***

Energy sustainability;
Solar-thermal systems;
Costing methodology;

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## 1. Introduction

The most recent conventions on climate change, together with the 2015 Paris agreement, have boosted the countries efforts to decarbonisation. According to Directive 2018/844 [1], almost 50% of final energy consumption is used for heating and cooling, being 80% of this energy used in buildings. Thus, each European Union (EU) member state must enforce actions to accomplish climate

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goals. To do so, the building stock should be renovated, mostly, by giving priority to energy efficiency and promoting the renewables' deployment. In consequence, a binding target of 32% energy from renewable sources at EU has been set for 2030 and an energy efficiency target of 32.5%.

The residential energy consumption (mostly space heating and Domestic Hot Water (DHW)) is affected by several factors, such as energy structure, urbanization level, technology used to cover the total energy load, energy prices, energy conversion efficiency, consumer habits and many others [2, 3]. Solar thermal systems are widely used to supply DHW and heating and it can be used in the domestic sector, services, industry or even at agriculture. An advantage of using solar thermal systems in industry is the presence of uniform industrial loads throughout the year, which often coincide with solar hours (*e.g.*, normal business hours of operation), resulting in better performance of solar energy collectors [4]. Karki *et al.* [5] provide decision support to small and medium-sized manufacturers in conducting a feasibility analysis for the application of solar flat-plate collector systems in their operations.

The use of solar heat in buildings can be segmented in terms of system size, ranging from smaller applications for single-family houses and medium size for multi-family houses [6,7], social amenities or commercial buildings. In 2009, Otanicar and Golden [8] compared environmental and economic impacts of using nanofluids to enhance solar collector efficiency as compared to conventional solar collectors for domestic hot water systems. Results show that, for the current cost of nanoparticles, the fluid-based solar collector has a slightly longer payback period. However, at the end of its useful lifetime, it has the same economic savings as a conventional solar collector. They use the life cycle assessment to evaluate the impact of a system on the environment from its initial resource allocation to its disposal/reuse after the consumer use phase. That study focuses on the major components of manufacturing, based on embodied energy, and operation of the solar collector [8]. Neves and Silva [9] explores the impact of the use of solar thermal systems with electricity backup and heat pumps as hot water suppliers in residential buildings, in small electric grids, using an hourly electricity backup load model. They conclude that the solar thermal systems are responsible for most of the peak load increase, but since they have the flexibility to adjust the electric backup hours (due to the thermal storage capacity), the impact on the grid can be minimized. Heat pumps on the other hand, albeit being more efficient in terms of electric backup, are less flexible to contribute to the grid management as they operate continuously.

In the European Union, many studies were developed to analyse the application of different solar energy systems to residential buildings. Martinopoulos and Tsalikis [10] presented a techno-economic evaluation of a solar system for space and water heating (with different collector sizes 8–12m$^2$ and different storage tanks 0.5–0.65 m$^3$) applied to isolated houses in Greece. Their study showed that these systems minimize the energy production costs with good results in terms of financial indicators (positive net present value and low payback periods). Afterwards, Tsalikis and Martinopoulos [6] evaluate with the implementation of the *f-chart* method, from the technical and economic point of view, different options regarding the installed capacity of photovoltaics and solar combi systems, in various locations and climatic conditions, in Greece. They conclude photovoltaic are able to cover the annual electricity demand of a residential building with a payback period of fewer than 7 years. Serban et al. [11] assessed the solar potential and the possibility of using solar energy to heat water for residential applications in Romania. They investigated the eco¬nomic potential of solar water heating systems and their contribution to saving energy and reducing $CO_2$ emissions. The results showed that if solar systems are used, the annual energy savings amount to approximately 71% and the reduction of greenhouse gas emissions into the atmosphere are of 18.5 tonnes of $CO_2$ over the lifespan of the system, with a discounted payback period of 6.8–8.6 years, depending on system characteristics, the solar radiation available, ambient air temperature and on heating load characteristics. These results indicate that investing in these systems is cost-effective for Romanian households as long as the government subsidies increase.

Gautam *et al.* [12] performed an extensive literature review about solar water heating systems and concluded that besides the development in terms of technical aspects, these thermal plants have a high initial cost as compared to the conventional solutions, which is the major barrier in becoming a common asset, so it is important to focus on their economics. Sami *et al.* [13] published an interesting study about the integration of solar water heating systems into high energy performance housing in Algeria, considering both energetic and economic analysis. The study aimed to calculate the optimal collector area that minimizes the installation costs and it was applied to different dwellings located at different regions with distinct climatic conditions. Datas *et al.* [14] applied a techno-economic analysis of solar photovoltaics (PV) for power-to-heat-to-power storage with trigeneration in the residential sector. This article assesses whether it is profitable to store solar electricity in the form of heat and convert it back to electricity on demand. The impact of a number of technical and economic parameters on the profitability of a self-consumption residential system located in Madrid is assessed. More recently, Louvet *et al.* [15] developed an economic comparison of reference solar thermal systems for households, in five European countries. The study aimed to calculate the heating cost of solar thermal systems per kWh of final energy. It was concluded that the heating cost differs widely, depending on countries and system types.

Important factors affecting the solar heat market include the costs of the systems and components, the solar irradiation, as well as, the characteristics of the infrastructures and buildings to integrate these systems [16]. In fact, and despite all the technological considerations, the cost of a solar-thermal system may vary by up to 20% from the average, depending on the collector design and building exposure to the sunlight [17]. Solar collectors typically supply 60% to 80% of the hot water needs, whereas the remaining 20–40% is provided by another heat source, usually electricity or gas [18].

In this study, a costing methodology was defined to estimate the capital costs of the main circuit of solar thermal system components, considering a residential reference case with a specific DHW needs, in the Portuguese context. The model includes the definition of three equations for each one of the main components: the solar collector, the pump and the storage tank. Each cost equation is defined considering size and quality variables based on technical and commercial data.

## 2. A brief review of solar thermal systems

In solar thermal systems, the solar radiation is converted directly into thermal energy through solar collectors, where the sunlight is absorbed and transferred to a fluid stream (*e.g.*, water or an antifreeze liquid) [17]. These systems also include a pump and a controller (in the case of active systems) and a storage tank to accumulate heat from the working fluid that circulates in the closed circulation pipes.

Depending on the application, heat can be required at low- and medium-temperature ranges (from 40 °C to 80 °C), which corresponds to the largest share of heat consumption in terms of DHW and space heating; or at high-temperature (from 80 °C to 200 °C) for different industrial process or power generation [5,17,19]. The solar collectors are therefore the key elements of the solar thermal systems because the collector technology should be able to meet the application needs at the lowest cost [15].

Solar thermal systems are divided into stationary collectors and tracking collectors that follow the trajectory of sunlight and can be classified by sun-tracking configuration, absorber type, concentration ratio (i.e. the ratio of aperture area to the absorber area of the collector), and temperature range [20]. The stationary collectors include the flat-plate collectors, the evacuated tube collectors and the compound parabolic collectors. The tracking collectors can have a single-axis tracking, which includes the linear Fresnel reflector, the parabolic and cylindrical trough collectors; or a two-axis tracking configuration as the parabolic dish reflector [5,12,20,21]. Several studies in the literature review the technical aspects of solar thermal systems with different collectors' configuration. Kalogirou [19] presented a review referring several types of solar thermal collectors and applications, such as flat-plate, parabolic trough, evacuated tube, Fresnel lens, parabolic dish and heliostat field collectors which are used in these systems. Ong and Tong [22] presented in their study a system composed by solar water heaters depending upon collector and storage tank design and sizing and weather conditions (solar radiation intensity and ambient temperature). Shelke *et al.* [23] presented a review of solar thermal systems identifying the most important aspects in designing direct and passive solar water systems. Suman *et al.* [20] in their review compiled the technological advances in the field of solar thermal technology with a focus on the description of different types of solar collectors and their specifications.

For domestic applications, the stationary collectors are the most used and the flat-plate collectors are the most appropriate for harvesting solar energy at low and medium-temperature ranges. A flat-plate collector consists of an absorber plate with a parallel back-plate with or without a transparent glass cover [20].

Abd-ur-Rehman and Al-Sulaiman [24] developed a simulation model taking into account parameters such as the solar radiation on horizontal and tilted surfaces, the solar fraction, greenhouse gas emissions and energy savings to compare the performance of evacuated tube and glazed flat-plate solar collectors. Results demonstrated that evacuated tube collectors are more advantageous than flat-plate collectors.

The unglazed collectors are cheaper but less efficient, whereas the flat-plate glazed collectors have lower convective and radiative heat losses, which improves their efficiency as well as the operating temperatures [20]. Alvarez *et al.* [25] developed a flat-plate collector, in which the absorber plate was exchanged by an array of recyclable aluminium cans painted black, achieving a thermal efficiency of 74%. Hossain *et al.* [26] studied solar water heaters and flat-plate thermal performance. Karki *et al.* [5] presented a technical and economic analysis regarding the feasibility of a solar thermal energy system using a flat-plate collector for industrial applications. In colder and foggy climates, the performance of flat collectors decreases, so vacuum tube collectors have developed, operating at temperatures in the range of 50 °C to 200 °C. It consists of several vacuum tubes connected together through a collection box containing insulation [20]. Otanicar and Golden [8] presented a comparative environmental and economic analysis of conventional (flat-plate collector) and solar hot-water technologies. The authors conclude for the need of a life cycle analysis in order to determine the energy payback time and energy return of investment. Lamnatou *et al.* [27] presented a study regarding a building-integrated solar thermal system based on vacuum-tube technology and considering a life-cycle analysis. They have compared a vacuum-tube collector with a flat-plate and the study revealed that the vacuum-tube system has better performance than the flat-plate configuration.

In 2002, about 12.3 million m$^2$ of solar collectors were installed in the EU, being Germany, Austria and Greece the strongest markets for solar thermal systems. In 2014, the European market suffered, once again, a reduction of the installed capacity, mostly due to the impact of the financial austerity and because of the deceleration of the construction building sector. Figure 1 shows the market for solar thermal systems in the EU28+Switzerland between 2009 and 2018. While the total installed capacity and the energy generation from solar heat continues to increase in Europe, the annual sales have contracted, mostly when referring to the installed capacity in terms of collector's area. According to European Solar Thermal Industry Federation (ESTIF), in 2018, the total capacity in operation increased to the value of 36.1 GW$_{th}$ (51.5 million m$^2$), adding by the end of 2018 of about 2.4% to the total installed capacity, when compared to the previous year. The annual sales totalled 1.5 GW$_{th}$, corresponding to an increase of 7.8% (approximately a total of 2.15 million m$^2$ glazed collectors). Also, the

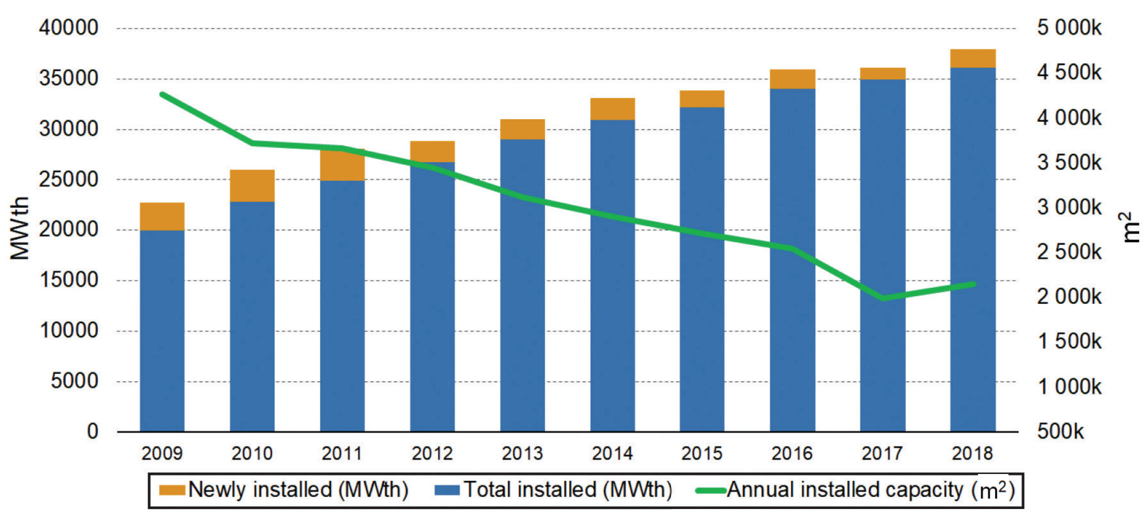


Figure 1: Total and newly installed capacity of solar thermal systems in EU28+Switzerland (glazed collectors) [28]

capacity in operation contributes to avoiding of about 6.8 Mt of $CO_2$ emissions. These late statistics report an important fact – Europe is back on track regarding solar heating and cooling sector growth [28].

Figure 2 shows the solar thermal capacity (per 1000 capita) of the 16 countries with the highest values compared to the EU28+Switzerland average [28]. In 2018, Cyprus, Austria, Greece, Denmark and Germany were the top five countries with higher solar thermal capacity in operation. According to the data, Germany remains, by far, the European country with the largest area of solar thermal systems installed and in operation (a total collector area of about 19.3 million m$^2$ by the end of 2018).

In Portugal, the year 2010 marks the beginning of the market contraction for solar thermal systems, which caused a continuous decline in this market until its stabilization in 2015. Figure 3 shows the evolution of

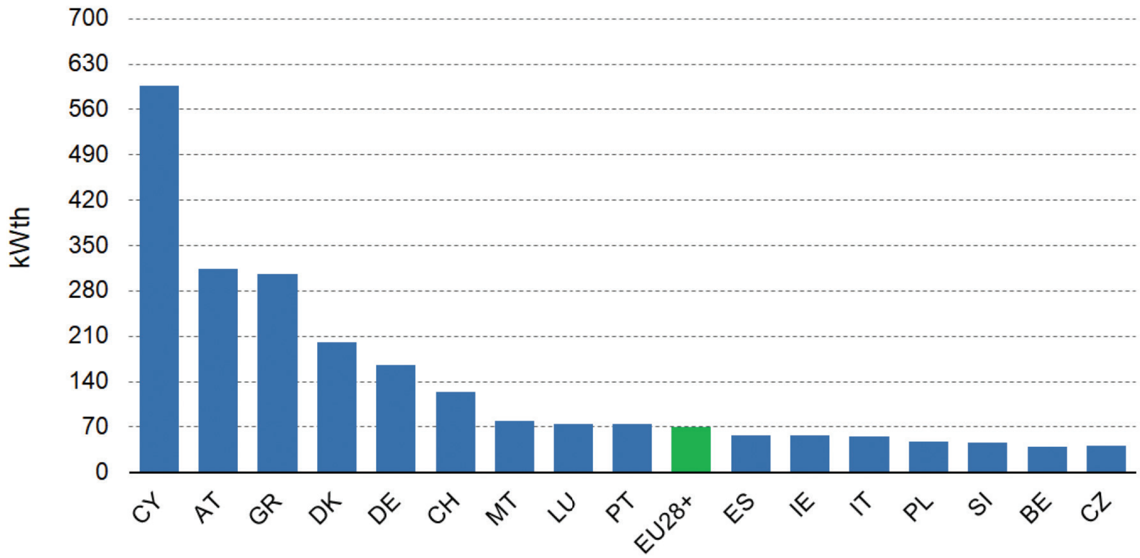


Figure 2: Solar thermal capacity in operation (per 1000 capita) of the 16 countries with the highest values compared to the EU28+Switzerland average, in the year of 2018 [28]

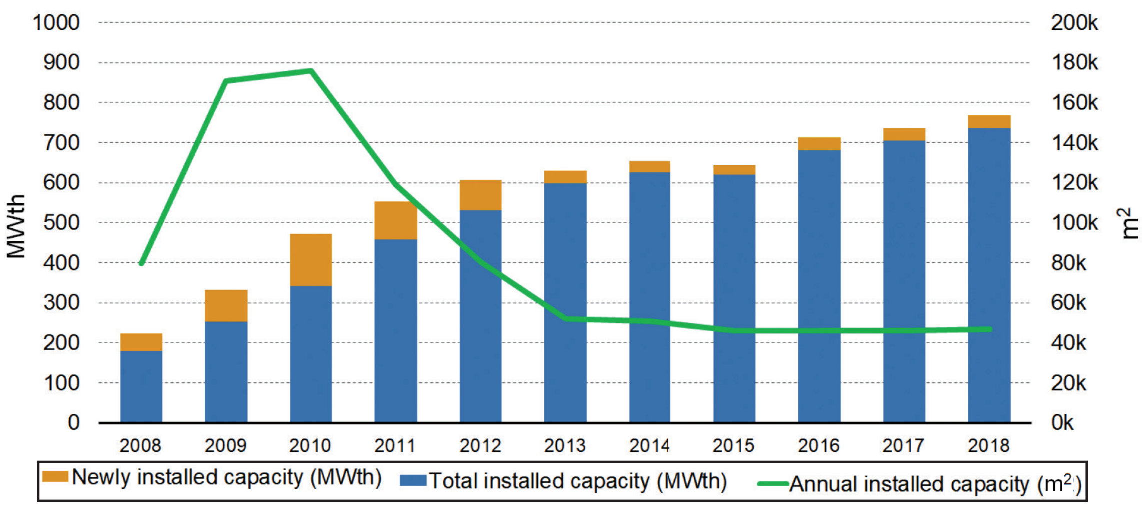


Figure 3: Total and newly installed capacity of solar thermal systems in Portugal (glazed collectors) [28]

total and newly installed capacity of solar thermal systems in Portugal between 2008 and 2018.

In Portugal, the incorporation of renewable energy sources increased in all sectors over the last decade due to the reformulation of energy policies. Also, the Portuguese solar thermal market seems to be more competitive for applications with bigger buildings. In 2018, an installed capacity of 47 000 $m^2$ (32 900 $kW_{th}$) was registered and the accumulated capacity reached the value of 1 098 552 $m^2$, corresponding to 768 986 $kW_{th}$ [28].

The distribution of installed systems is divided between the thermosiphon, forced convection systems, and individual collectors. The thermosiphon represents 22%, the forced convection systems 25% and the individual collectors correspond to 53%. Regarding individual collectors, about 83% of them are used in residential dwellings and only 17% is used in public services such as swimming pools and hotels [29].

Several support measures for solar thermal in Portugal are related to the target of the renewable share of 40% by 2030, in order to reduce energy dependence from abroad, contribute to increase the energy efficiency of buildings, and reduce the contribution of heating to the invoice of electricity [30]. Consequently, the definition of economic models that consider both the energy requirements and the technical specifications of the thermal systems, allows evaluating the savings from its acquisition and further operation.

## 3. System description

When sizing a solar thermal system for a certain energy consumption profile, the most important components are the solar collector, the storage tank to accumulate heat and the pump with its controller. Figure 4 discloses a representative scheme of the main circuit of a solar thermal system.

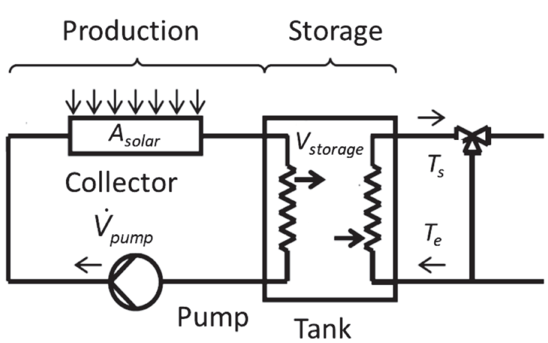


Figure 4: Scheme of the main circuit of the solar thermal system

The useful power ($P$) collected by the thermal fluid of a solar thermal system can be estimated by the correlation between the effective solar collector area ($A_{solar}$), solar irradiation ($I_g$), collector aperture transmittance (τ), collector absorbance (σ), the global losses coefficient ($U_L$) and the temperature variation between the thermal fluid mean temperature (15°C $\leq t_f \leq$ 180°C) and the ambient temperature (which is assumed to be a fixed temperature, $t_a =$ 15°C). If the mean temperature of the fluid is directly used, it is necessary to include a correction factor, also called as the irrigation factor ($F'$), which reduces the useful power (see equation (1)).

$$P = A_{solar} \cdot F' \cdot \left[ I_g \cdot \tau \cdot \sigma - U_L \left( t_f - t_a \right) \right] \quad (1)$$

The solar collection efficiency is defined by the ratio between the captured and the received energy [31]. So the efficiency ($\eta_{collection}$) can be calculated as the equation (2):

$$\eta_{collection} = F'(\tau\alpha) - (F'U_L)T^* - (F'U_L)I_g\, T^{*2} \quad (2)$$

where F'UL correspond to the linear losses coefficient and the term T* represents the maximum temperature that the collector can reach for certain ambient temperature and solar irradiation ($t_f - t_a / I_g$). When solar energy is enough to increase the thermal fluid temperature and the heat transfer process is guaranteed, water circulates from storage to the collector. Then, the heated water returns to the storage tank, where it is stored until it is needed. As the pump circulates the water, the collectors can be assembled either above or below the storage tank [31].

The mass flow that is pumped in the primary circuit depends on the collection aperture area and the thermal properties of the thermal fluid that is used in the system, the specific heat ($c_p$) and the density ($\rho_{tfluid}$), as presented in the equation(3). Usually, the thermal fluid used in the primary circuit is a mixture of antifreeze with water in appropriate concentrations to the minimum temperature of a certain location [21,32].

$$\dot{V}_{pump} = \left( \frac{10F'U_{L0}}{c_{p\ tfluid}} \cdot A_{solar} \cdot 3600 \right) \cdot \frac{1}{\rho_{tfluid}} \quad (3)$$

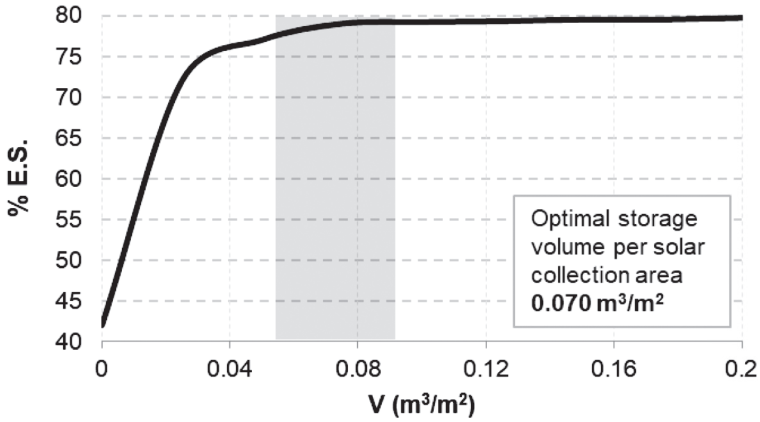


Figure 5: Relationship between the efficiency of solar energy (%E.S.) usage and storage capacity. Adapted from [31]

The need for energy does not always coincide with the time of production, so it is necessary to have an accumulation system to meet the demand in times of low radiation or no consumption. The use of vertical tanks has the advantage of favouring water stratification. Thus, it is ensured that the hottest water is in the upper part of the accumulator, which is precisely where it is extracted. There is a correlation between the percentage of incident solar energy use and the optimum volume ($V_{storage}$) of the deposit per unit area of the solar collector, as presented by the equation (4).

$$0.060\, m^3/m^2 < \frac{V_{storage}}{A_{solar}} < 0.090\, m^3/m^2 \qquad (4)$$

According to Lebeña and Costa [31], the optimal storage volume per unit of solar collection area is 0.070 $m^3/m^2$. As presented in Figure 5, values above 0.080 $m^3/m^2$ do not lead to greater use of incident solar energy, but only contribute to the increase in the storage tank volume and its cost [31].

## 4. Costing methodology to estimate capital costs of solar thermal systems

As stated by Tronchin et al. [33], the analysis of the cost-optimal level of a thermal system corresponds to a "balance point" between the initial investment cost and the annual energy-cost, during a certain period of evaluation. In that sense, it is important to define the economic criteria that allow evaluating an investment from the financial and macroeconomic viewpoints.

The costing methodology consists of the derivation of a cost expression for each component by integrating cost coefficients and thermodynamic variables adjusted for a certain technology, taking into account real market data [34]. Each cost equation is defined considering size and quality variables. The equations are defined considering that the cost of each component includes a cost coefficient, a reference size factor that scales the component and, for some system components, a quality factor. The basic formulation is presented by the equation (5):

$$C_i = C_{ref,i}\, F_{ref} \cdot \left(\frac{F_i}{F_{ref}}\right)^b \qquad (5)$$

where the term $C_{ref,i}$ is the reference cost coefficient, corresponding to a cost per unit of one (or more) physical parameter and the variables $F_{ref}$ and $F_i$ are the reference value and the physical variable value, respectively. The term represented by $b$ is the sizing exponent. A cost equation was defined for the three main components of the system: the solar collector, the pump and the storage tank.

### 4.1. Solar collector cost equation

The purchase cost of the solar collector ($C_{solar}$) is affected by two main variables: the solar collector area and the collection efficiency. The collector cost equation is given by the equation (6):

$$C_{solar} = C_{ref,solar} \cdot A_{ref,\,solar} \cdot \left(\frac{A_{solar}}{A_{ref,\,solar}}\right)^{b_{solar}} \cdot C_{\eta_0} \qquad (6)$$

where $C_{ref,\,solar}$ is the reference cost coefficient, with a constant value of 258 €/$m^2$, $A_{solar}$ represents the collector area [in $m^2$] and $A_{ref,\,solar}$ is the reference collector area (2.5 $m^2$). The equation also includes a sizing factor ($b_{solar}$) which was assumed to be 0.3.

The equation integrates an additional term $\left(C_{\eta 0} = \eta_0^{\alpha} \cdot a_1^{\beta}\right)$ that accounts the efficiency in the cost estimation, which can be calculated as the product between the efficiency factor ($\eta_0$) and the linear loss coefficient ($a_1$). The exponents α and β were obtained by non-linear regression. The efficiency was considered in the definition of the purchase cost equation because, according to a preliminary study, there is a relationship between the specific cost of a solar collector and its efficiency. The specific cost of solar collectors of different commercial models considering their efficiencies (Figure 6) shows that collectors with higher efficiencies have higher specific costs. Thus the capital cost of the solar collector estimation depends on two main technical variables as disclosed by Figure 7.

### 4.2. Pump cost equation

The purchase cost equation of the circulation pump, ($C_{pump}$) is defined considering the flow rate ($V_{pump}$) as the main operational variable affecting the cost of this component (equation(7)). The term $C_{ref,\ pump}$ corresponds to the constant reference cost of the pump cost, $V_{ref,\ pump}$ [in $m^3/h$] is the reference flow rate and $b_{pump}$ is the sizing exponent. The reference cost coefficient is equal to 322.45 €/$m^3$/h, the reference flow rate was assumed as 0.98 $m^3$/h and the sizing factor was set at 0.6.

$$C_{pump} = C_{ref,pump} \cdot \dot{V}_{ref,pump} \left( \frac{\dot{V}_{pump}}{\dot{V}_{ref,pump}} \right)^{b_{pump}} \tag{7}$$

### 4.3 Storage tank cost equation

Regarding the storage tank cost equation, the physical variable that mostly affects its price is the storage volume ($V_{storage}$) [in $m^3$], as presented in equation(8):

$$C_{storage} = C_{ref,storage} \cdot V_{ref,storage} \left( \frac{V_{storage}}{V_{ref,storage}} \right)^{b_{storage}} \tag{8}$$

where the reference cost coefficient $C_{ref,\ storage}$ is 3 506 €/$m^3$ and the reference storage volume, $V_{ref,\ storage}$, is assumed to be 0.32 $m^3$. After a sensitivity analysis, the sizing factor $b_{storage}$ was defined as equal to 0.5.

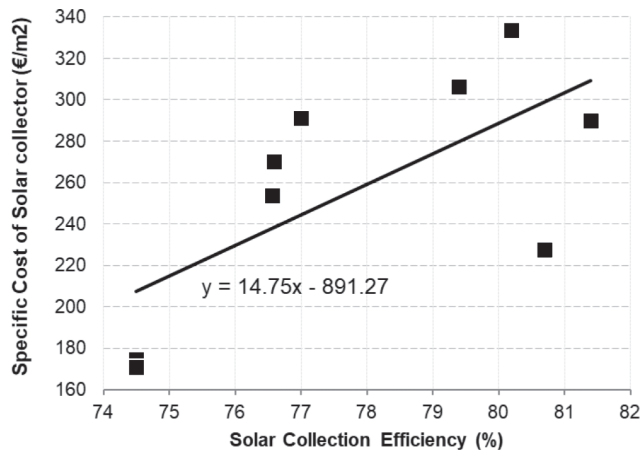


Figure 6: Specific cost of solar collectors of different commercial models, considering their specific efficiencies.

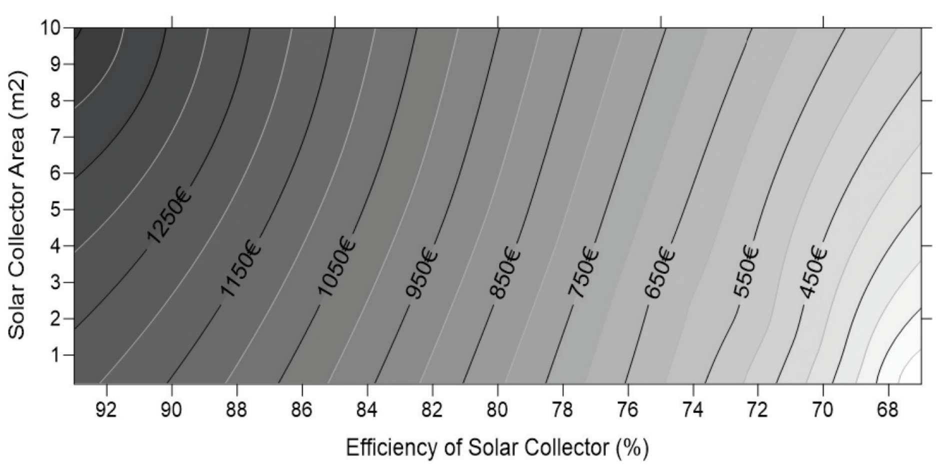


Figure 7: Cost estimation of the solar collector as a function of the collector area and its efficiency

### 4.4. Total investment costs

The capital investment of the components corresponds to the sum of the purchase cost of the pump, storage tank and the solar collector costs. The estimated cost regarding the engineering expenses with the installation ($C_{installation}$) usually represents a relative percentage of the main components investment. Thus, the total investment costs are calculated by the equation(9):

$$C_{inv} = C_{pump} + C_{storage} + C_{solar} + C_{installation} + C_{circulation} \quad (9)$$

where the $C_{installation}$ was assumed to be 10% of the total cost of system components. The circulation costs ($C_{circulation}$) were defined as a fixed value, since, for the range of individual domestic applications, the prices do not vary significantly [21].

## 5. Validation of costing methodology and results

In this section, the validation of each component cost equation is presented considering different data from different commercial models available in the market The validation is performed considering the relative error from the real cost and the estimated cost. In addition, the results of the economic model applied to a reference case scenario are presented. The reference case scenario corresponds to a residential building with specific energy consumption located in Lisbon (Portugal).

### 5.1. Validation of the cost equations

The development of a correct methodology to define the cost equations for each component of a thermal system is a very demanding process because most manufacturers do not provide important information concerning the technical specifications and much less information about production costs. The cost coefficients of each thermal component were calculated and represent the relative weight that it is attributed to each component in the final purchase cost of the thermal plant. The choice of cost coefficients and sizing factors values was based on technical information from commercial systems and sensitivity analysis.

Thus, the purchase cost and technical data of several commercial models were used to validate the cost equations of solar collector, pump and storage tank, as presented by Table 1, 2 and 3. The cost of each component was estimated taking into account the nominal values of operating values. The relative error between the estimated and the commercial cost was also determined in order to have a measure of model precision. For all the tested solar collector models, the relative error is lower than 8%, showing a good correlation between the costing equations and the purchase cost of real models.

### 5.2. Reference case for model validation

In order to validate the costing methodology, a residential dwelling located in Lisbon was considered. Assuming an occupation of 4 people with a need of 40 L of water per day and per person, at a temperature of 60 ºC, the daily hot water consumption can be determined.

A simplified methodology was applied to estimate the energy requirements in terms of domestic hot water needs of a building (reference case). The thermal load was calculated according to the Portuguese regulation for the thermal behaviour of buildings (Decree-Law 118/2013) [37] that complies with the Energy Performance of Buildings Directive (EPBD).

**Table 1: Validation of the solar collector cost equation considering several commercial models [35,36]**

| Solar Collector | | | | | | |
|---|---|---|---|---|---|---|
| **Commercial Model** | **Commercial Cost (€)** | **Collector Area ($m^2$)** | **Efficiency Factor (η0)** | **Linear loss coefficient ($W/(m^2K)$)** | **Estimated Cost (€)** | **Relative Error** |
| gIGAsOL | 684.0 | 2.70 | 0.766 | 3.433 | 630.2 | 7.86% |
| FKC-2 W | 690.0 | 2.37 | 0.770 | 4.615 | 636.4 | 7.76% |
| FKC-2 s | 640.0 | 2.37 | 0.766 | 4.216 | 625.0 | 2.34% |
| FKT-2W | 654.5 | 2.55 | 0.802 | 5.833 | 698.4 | 6.71% |
| SOL250 BAXI | 727.0 | 2.51 | 0.814 | 4.908 | 686.3 | 5.60% |

**Table 2: Validation of the pump cost equation considering several commercial models [35,36]**

| Pump | | | | |
|---|---|---|---|---|
| **Commercial Model** | **Commercial Cost (€)** | **Flow Rate ($m^3/h$)** | **Estimated Cost (€)** | **Relative Error** |
| GiroMax Solar 15/60 | 235.0 | 0.65 | 244.0 | 3.84% |
| GiroMax Solar 15/70 | 293.0 | 0.80 | 284.6 | 2.86% |
| GiroMax Solar 25/70 | 303.0 | 1.00 | 316.0 | 4.29% |
| GiroMax Solar 25/60 | 344.0 | 1.10 | 334.6 | 2.73% |

**Table 3: Validation of the storage tank cost equation considering several commercial models [35,36]**

| Storage tank | | | | |
|---|---|---|---|---|
| **Commercial Model** | **Commercial Cost (€)** | **Volume ($m^3$)** | **Estimated Cost (€)** | **Relative Error** |
| SOLAR INOX 444 TS 150L | 789 | 0.150 | 768.1 | 2.6% |
| Junkers 400 - ZB | 1 200 | 0.379 | 1 221.0 | 1.8% |
| Vulcano SK 500-1 | 1 363 | 0.449 | 1 329.0 | 2.5% |
| Junkers 500 - ZB | 1 300 | 0.465 | 1 352.4 | 4.0% |

**Table 4: Input parameters to calculate the thermal requirements for DHW**

| Parameter | Value |
|---|---|
| Daily hot water consumption, $Cons_{DHW}$ | 160 L/day |
| Temperature of DHW, $T$ | 60 ºC |
| Yearly sum of global irradiation (Lisbon), $I_g$ | 1 890 kWh/$m^2$ |
| Yearly energy to produce DHW, $Q_{DHW}$ | 2 037 kWh/year |

Considering a solar panel optimally oriented, 45° south, and set with an inclination of 51° angle, the specific daily hot water consumption can be also calculated by taking into account the ratio between the daily water need per person, divided by the number of the building residents [38]. Thus, the yearly energy required to suppress the DHW needs ($Q_{DHW}$) can be calculated by the equation(10):

$$Q_{DHW} = Cons_{dhw} \cdot (4.187/3600) \cdot \Delta T \cdot 365\, days \tag{10}$$

where $\Delta T$ is the temperature increase from the grid water temperature. Table 4 summarizes the values of thermal requirements for DHW.

The energy required to suppress the DHW needs is approximately 2 037 kWh/year. According to [31], at least, an equivalent area of 1 $m^2$ of solar collection is required to suppress a demand of 500 kWh/year, and thus, a solar collector with a minimum area of 4 $m^2$ should be required. Based on this calculation, a reference case scenario (Table 5) can be defined based on the minimum acceptable value of storage capacity and pump mass flow assuming a linear losses coefficient $F'U_{L0}$ of 3.6844 W/($m^2$.K) and as thermal fluid a solution of water plus 22.5% of propilenoglycol ($\rho_{tfluid}$ = 1.19x$10^3$ kg/$m^3$, $c_{p\ tfluid}$ =4.045 kJ/(kg.K)) [38].

**Table 5: Reference values of the case scenario for model validation**

| Variable | Value |
|---|---|
| Solar Collector Area, $A_{solar}$ | 4$m^2$ |
| Solar collector efficiency factor, η0 | 0.74 |
| Linear loss coefficient, $a_1$ | 3.50 W/($m^2$K) |
| Pump mass flowrate, $_{pump}$ | 1.10 $m^3$/h |
| Storage tank Volume, $V_{storage}$ | [0.24 $m^3$; 0.36 $m^3$] |

## 5.3 Results and discussion

Table 6 shows the results of the economic model for this reference case scenario, assuming the minimum acceptable value of storage capacity. For a storage tank with a capacity of 0.240 $m^3$ and a solar collector with 4 $m^2$, the total investment costs are of about 2 812.6€, which represent a specific cost of 703.2 €/$m^2$. These results are consistent with the commercial data, which shows that the prices of active systems start at 2 500 € for single

**Table 6: Results of the economic model (storage tank 0.24 m$^3$)**

| Components | Cost |
|---|---|
| $C_{solar}$ | 791.7 € |
| $C_{storage}$ | 971.6 € |
| $C_{pump}$ | 339.1 € |
| $C_{installation}$ | 210.2 € |
| $C_{circulation\ system}$ | 500 € |
| $C_{inv}$ | 2 812.6 € |
| *Specific cost* | 703.2 €/m$^2$ |

**Table 7: Results of the economic model (storage tank 0.36 m$^3$)**

| Components | Cost |
|---|---|
| $C_{solar}$ | 791.7 € |
| $C_{storage}$ | 1 190.0 € |
| $C_{pump}$ | 339.1 € |
| $C_{installation}$ | 232.1 € |
| $C_{circulation\ system}$ | 500 € |
| $C_{inv}$ | 3 052.8 € |
| *Specific cost* | 763.2 €/m$^2$ |

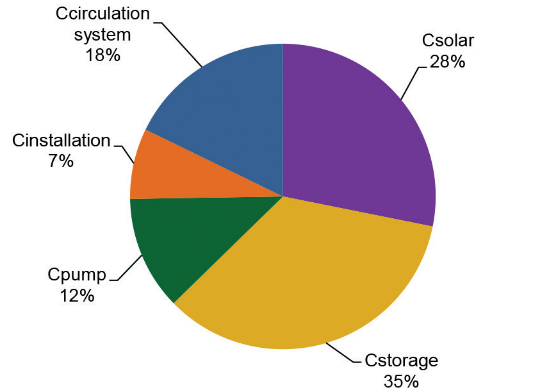


Figure 8: Breakdown of the investment costs (storage tank of 0.24 m$^3$)

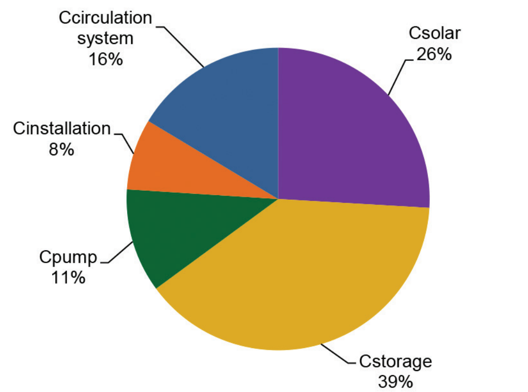


Figure 9: Breakdown of the investment costs (storage tank of 0.36 m$^3$)

dwelling buildings. Regarding the breakdown of the investment costs (Figure 8), the solar collector and storage tank are the most expensive components of the thermal systems, representing 28% and 35%, respectively. The installation cost represents 7% of the capital cost of the thermal system components. The cost of installation varies with access to the installation site (terrace or roof), the size of the system and the distances for the electrical connections to the hot and cold water streams.

Table 7 and Figure 9 present the results for the economic model for the same reference scenario, only considering a storage tank of 0.36 m$^3$. For this technical option, there is a 9% increase in the investment costs of the solar thermal system, but the system allows the accumulation of twice the volume of hot water. In this way, the definition of a cost methodology to estimate the capital investment of thermal systems, based on technical parameters, gains greater applicability.

The results for this case scenario show that for a solar-thermal system with a 4 m$^2$ collector, located at Lisbon, optimally-inclined and south-oriented plant, the system's specific cost ranges from 703.2 €/m$^2$ to 763.2€/m$^2$, depending on the acceptable storage tank capacity.

Considering only the avoided cost of producing the same amount of heat (2 037 kWh per year as DHW) by other types of technologies, by using different fuels, the payback period of the investment costs of the solar thermal system can be estimated. To do so, the cost of Natural Gas (NG), diesel and electricity for heat production was assumed to be 6.22 cent€/kWh, 9.69 cent€/kWh and 17.32 cent€/kWh, respectively. Based on these assumptions, Table 8 presents the economic value of the heat produced to suppress the yearly DHW considering the use of alternative fuels and the respective payback period of the solar thermal system investment assuming the avoided cost of producing the same amount of heat. This simple analysis shows that if a solar thermal system was installed replace a system using electricity, it would be possible to recover an investment cost of 2 812.6 € within a period of 8 years, simply accounting the avoided cost of using other fuels.

**Table 8: Economic value and the payback period of the energy produced to suppress the yearly DHW considering the use of other fuels and assuming the avoided cost of producing the same amount of heat (2 037 kWh/year)**

| Alternative fuels | Cost of alternative fuel (cent€/kWh) [39] | Economic value of produced heat (€/year) | Payback period (years) |
|---|---|---|---|
| NG | 6.22 | 126.7 | 22.2 |
| Diesel | 9.69 | 197.4 | 14.2 |
| Electricity | 17.32 | 352.8 | 8.0 |

This study is in line with several others applied to countries such as Greece or Spain [10,23,40,41]. The high solar radiation values registered in these countries positively contributes to the implementation of solar thermal systems in the building sector. As stated by Martinopoulos and Tsalikis [10], the use of solar thermal systems for space and water heating enables the minimization of energy costs and, in some cases, the systems are capable of covering more than 40% of the total building energy load. Nevertheless, further analysis needs to be included regarding the inclusion of thermal storage solutions that shift energy over hours, or even a full day to overcome the intermittency of solar energy.

## 6. Final remarks

The paper presents a costing methodology able to estimate the capital cost of solar-thermal systems as a function of the system size and a specific application. The model was validated for a reference dwelling in Lisbon, with an occupation of 4 people with an estimated DHW need of 2 037 kWh/year. For this application, it is required at least 4 m$^2$ of solar collector and the system cost ranges from 703.2 €/m$^2$ to 763.2 €/m$^2$, depending on the acceptable storage tank capacity (between 0.24 m$^3$ and 0.36 m$^3$). These values represent investments costs varying between 2 812.6 € and 3 052.8 €, which are in agreement with the data from the solar systems market since the prices of active systems start at 2 500 € for single dwelling buildings.

According to the Portuguese Association of Renewable Energy (APREN) [42], in 2018, 55.1% of Portugal's electricity demand was produced by renewable energy sources, which allowed a reduction of 6 million tonnes of $CO_2$ emissions from the power production sector and to save 1.27 billion of euros in fossil fuel imports. However, solar thermal was responsible for only 1.7% of that energy. Therefore, there is a great market opportunity for solar technologies and one of the aspects contributing to this low values is the difficulty of evaluating the effective savings that allow the recovery of the capital invested in the acquisition of such systems. In that sense, these models are a valuable tool, mostly when a good correlation between the cost results and the commercial data is achieved.

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