AVALIAÇÃO DO IMPACTO ENERGÉTICO DE SISTEMAS SOLARES TÉRMICOS

EXTENDED ABSTRACT

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1. Introduction

Renewable energy is a solution to many social problems related to fossil fuel consumption. It can help improve living standards, especially in countries without oil reserves, like Portugal. By using renewable energies, these countries reduce both their economic dependency and the negative impacts of burning fuels during their use.

Residential units have an important role in energy consumption: in developed countries, they account for between 20% and 40% of total energy consumed [1]. Despite solar radiation being more than 50% above the average for Europe, Portugal spends almost 30% [2] of its energy budget on domestic water heating (DWH). This can be reduced through solar energy usage.

Several programmes and legal measures have been implemented in Portugal and in Europe generally to promote the use of renewable energies. Currently, the use of solar panels is mandatory in all new constructions, extensions or major house rehabilitation works in Portugal. Bu other forms of renewable energy can be used. These are not widely used, though.

In this context, it is essential to evaluate the energy performance of several solar thermal systems to be able to choose the most appropriate components and parameters for a specific situation. Many researchers believe that the best way to obtain information about a specific system is through experimental measurement. However, a theoretical approach or computer modeling can have several advantages, including the possibilities of analysing the impact of several parameters such as climatic conditions and system configurations or predicting the solar heating system's behaviour over a long period of time.

In this project, computer modelling was performed with the Solterm and EnergyPlus programs. Other authors [3, 4] have used other software, e.g. TRNSYS.

EnergyPlus has been used more often for overall building energy simulations [5, 6] than for domestic hot water (DHW) systems. Altoé et al [7] used this software to design and simulate solar thermal systems to answer the different levels of comfortable bathwater and energy efficiency in buildings using electric energy for DHW.

Solterm was chosen because it is analyses the development of a solar system through the numerical simulation of energy balances over a reference year. Furthermore, it was specially designed for the technical and weather conditions prevailing in Portugal. Several researchers have used this software, including [8, 9, 10, 11, 12].

These studies show that research related to centralised DHW systems has been carried out in Portugal. However, other studies, sometimes on a larger scale, have been carried out in other countries. These include Michaelides and Eleftheriou [13], who examined the behaviour of an STS with a 3 m^2 flat plate collector and a 68 litre storage tank in Cyprus, using the data from a two-year period.

Ayompe et al. [14] presented the results of monitoring the energy performance of two solar thermal systems, one with a flat plate collector and the other with an evacuated tube collector. Shi et Al. [15] addressed the inclusion of centralised DHW systems in multifamily buildings in China because of the existing conditions like shade, coverage area and using of interior areas, caused by the high population density. Furthermore, the authors propose solutions that aim to exploit solar thermal projects for building facades.

For their part, Mugnier and Seleme [16] studied a solar thermal system with a decentralised storage solution and presented the energy balance over two years. They concluded that these systems spend less on back-up energy than the centralised ones. A centralised storage system showed a solar fraction of 23.5%, the decentralised one showed a solar fraction of 45%.

Solar systems can be certified in a multifamily building, or in a neighbourhood or even in a region. Theoretically, the bigger the system the larger the gains. For example, in the study by Moià-Pol et al. [17], a heating and cooling system was designed for a tourist area in Palma Beach, Mallorca, with a collector area of approximately 200,000 m^2. The conclusions were that the investment payback would be achieved in about 10 years.

In the study by Bøhm [18], DHW efficiency in national distribution systems was documented based on an analysis of current conditions. However, some more energy efficient and environmental friendly solutions were also proposed.

This paper reports both the study of the energy performance through simulation programs and a financial analysis, including the determination of financial indicators. They are based on the comparison between a solar thermal system and a DHW system equipped with a conventional energy source, in this case, electricity. Other studies [19, 20, 21] report comparisons drawn not only with solar thermal systems and conventional electricity systems, but also with a conventional gas boiler system.

The purpose of this study was to evaluate and quantify the impact of solar thermal systems in multifamily buildings with different configurations, in Portugal. For this, the systems used and their components were studied. Three studies were carried out, two through the simulation programs EnergyPlus and Solterm, the third being a financial analysis.

2. Methodology

The complexity of large DWH systems has led to the appearance of a wide variety of different solutions, consistent with the details of each project. These differences occur in solar collection, in storage options and in the location of the auxiliary heating system.

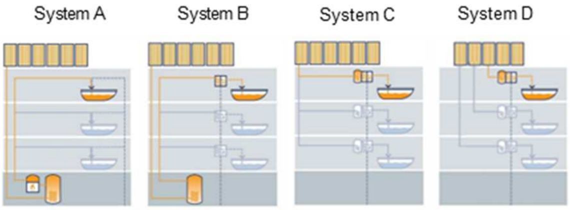

Fig. 1. DHW Systems for multifamily buildings

The final solution is directly influenced by factors like the distribution of different types of apartments per floor and division between common and private areas.

The configuration of solar system installations varies from country to country in Europe, according to the heating needs. Based on [22] and [23], we can categorise 4 different configurations (Fig. 1. DHW Systems for multifamily buildings
 and **Erro! A origem da referência não foi encontrada.**):

- System A – Centralised solar collection, water storage and auxiliary heating system;
- System B – Centralised solar collection, water storage and individualised auxiliary heating system;
- System C – Centralised solar collection and individualised water storage and auxiliary heating system;
- System D – Individualised solar collection, water storage and auxiliary heating system.

2.1. Case Study

The studied solar thermal systems belong to a building in the north of Portugal, in Porto (Lat. 41,16ºN, Long. 8,62º W). It is a multifamily building containing 20 units, 10 of which are T2 (2 bedrooms) and the other 10 are T4 (4 bedrooms), making a total of 80 DHW consumers. A daily consumption of 40 litres per person was assumed, amounting to 3200 litres per day for all the building. Since the Portuguese building energy regulations indicates a temperature of 15ºC for water in the public network, a rise of 35ºC, to 50ºC, was assumed for water heating and storage.
The building's roof is flat with an area of more than than 300 m^2. No shading of the solar collectors was considered, and the azimuth of the collectors is south.

2.2. Solterm

Solterm is a program that analyses a solar system's performance by stages [24]. It was developed by *Laboratório Nacional de Energia e Geologia* (Portuguese National Laboratory of Energy and Geology). As already mentioned, this program is taken as a reference for the calculations of Portuguese building energy regulations [25]. This software was specially created for Portugal's technical knowhow and weather conditions and had two fundamental components: the solar thermal systems, and the photovoltaic solar systems. The version used in this work was the 5.1.4.
The first study used the simulation program Solterm to analyse the influence of some system components. Some components were fixed and others were varied with the aim of finding the best overall solution for the case study. The systems that were conceived according to Portuguese regulations were validated afterwards. Finally, a sensitivity analysis was performed on the catchment area and the volume of storage (Fig. 2)

2.3. EnergyPlus

EnergyPlus is a program that simulates the thermal and energy performance of a building and calculates several parameters, particularly the heating and cooling needs, illumination and ventilation. With respect to solar collectors, EnergyPlus allows the user to model the entire system from the solar collector's characteristics and type of storage tank to the demand profile and all the instructions for the controller.
This software was chosen not only for comparison of the results obtained in Solterm but also because it is an open source program widely used internationally.

2.4. Financial Analysis

Financial analysis is always a fundamental factor in every decision in a project since a solution is only useful if it offers a competitive price that makes it viable. In this context, some indicators were calculated to describe the system's financial impact and help future designers, promoters and users.

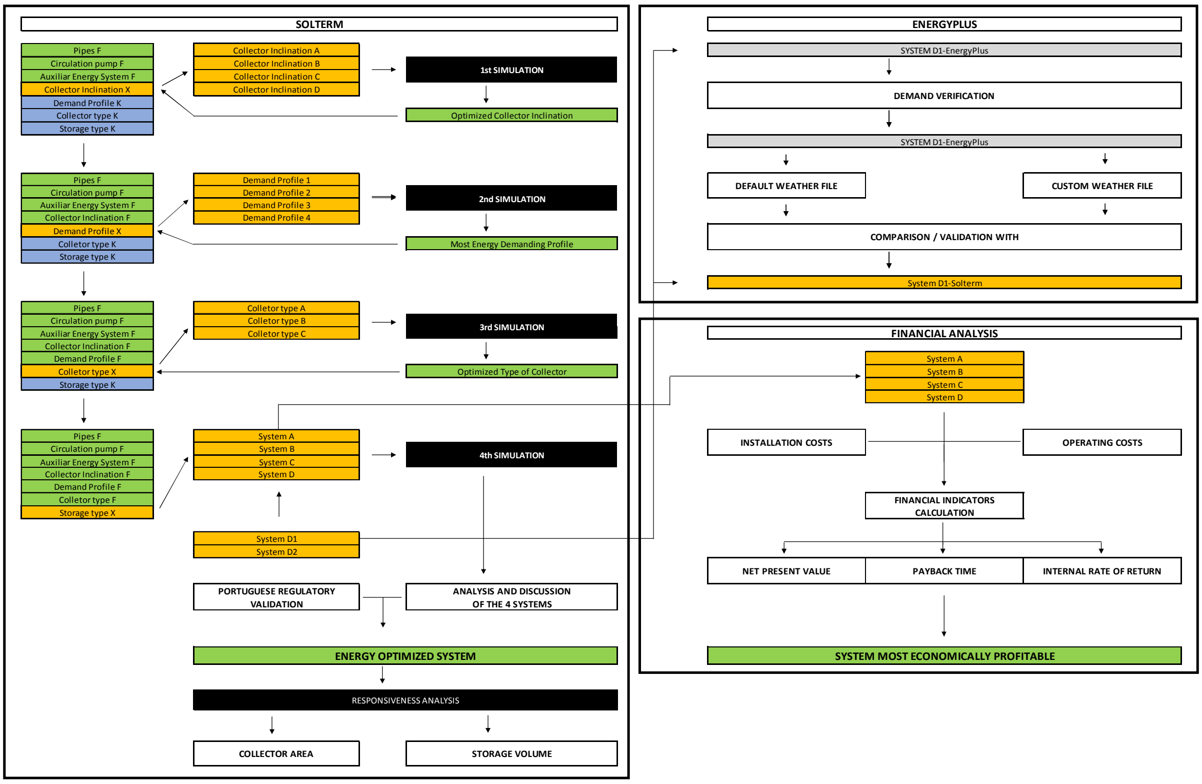

Fig. 2. Methodology used for analyses

3. Results & Discussion

3.1. Solterm

In order to obtain results that translate into considerable energy gain and a useful reduction in CO_2 emission, the aim was to reach a minimum overall solar fraction of 70%.

It was decided to split the components into two groups: i) the components that remained unchanged throughout; ii) the components that were varied in order to analyse their influence on system performance. The unalterable components were: i) the auxiliary heating system (electricity); ii) recirculation pump; iii) percentage of antifreeze liquid, and iv) tube dimensions. The last three are presented in the next section.

The variable components were: i) collector's inclination; ii) demand profile; iii) type of collector, and iv) storage method (storage tank group).

To study the components better, they were changed one by one, with the rest remaining fixed in every group of simulation.

Table 2 summarizes all the simulations performed with Solterm.

3.1.1. Fixed Components

The components unchanged throughout the whole study were the circulation pump, the percentage of antifreeze liquid and the tube sizes.

Regarding the circulation pump, it is useful to calculate the specific flow. Consequently, all the flows were estimated in every utilization device, showers, bathtubs, lavatories, bidets, dishwashers, and a specific flow of 26,6 $l/h/m^2$ was obtained.

The percentage of antifreeze in the mixture is related to the temperatures in the study zone, given that a percentage of antifreeze lowers the freezing temperature of the fluid, therefore protecting the equipment. The program suggests a figure of 25%, which was the one used.

Regarding the tubing, the exterior section, which has mechanical protection because of its location,, was considered to be 40 m long and in the interior one 50 m, making a total of 90 m of tubing.

3.1.2. Simulation 1 – Collector Inclination

The collectors' inclination is determined by the type of use and the time of the year. In order to determine it, it was recommended a fixed inclination, calculated and optimized in the Solterm program.

As already mentioned, this simulation considered a number of fixed parameters (Table 1). Flat plate collectors, with a collector area of 80 m^2, were assumed, allowing 1 m^2 per user [25]. The System used was System A, with the centralised solar collection, storage and back-up system. It also has two 1500 L Buderus storage tanks, with an internal exchanger. The demand profile considered has a 100% daily consumption between 17h and 18h.

The solar collector angles were set for summer users (26º), winter users (56º) and annual users (36º), according to the indications in [26], and, in the last case, the perfect inclination determined by the simulation program.

Fig. 3 shows the incident solar energy during the year according to the collectors' inclination.

Table 1

	SIMULATION 1	SIMULATION 2	SIMULATION 3	SIMULATION 4
Collectors				
Inclination	*variable*	39º	39º	39º
Type	Flat plate collector	Flat plate collector	*variable*	Flat plate collector
Azimuth	South	South	South	South
System	System A	System A	System A	*variable*
	Collector Area, Storage Tank and Auxiliary Energy System - Centralized	Collector Area, Storage Tank and Auxiliary Energy System - Centralized	Collector Area, Storage Tank and Auxiliary Energy System - Centralized	
Storage Tank				*variable*
Type	2 x DHW Storage Tank (1500 L)	2 x DHW Storage Tank (1500 L)	2 x DHW Storage Tank (1500 L)	
Heat Exchanger	Internal	Internal	Internal	
Efficiency	55%	55%	55%	
Demand Profile	Profile 3	*variable*	Profile 1	Profile 1
	17h - 18h		Morning 70%	Morning 70%
	3200 L		Evening 30%	Evening 30%
	-		3200 L	3200 L
Simulation focus	Which is the optimized inclination?	Which is the most energy-demanding profile?	Which is the optimised type of colletor?	Which is the optimized form of water storage?
	26º	Profile 1 *70% Morning, 30% Evening*	Unglazed plate collector	System A 2 x DHW Storage tank (1500 L)
	36º	Profile 2 30% Morning, 70% Evening	Flat plate collector	System B 2 x Inertia Storage tank (1500 L)
	39º		Evacuated tube collectors	
	56	Profile 3 Uniform ~4,17% per hour		System C 20 x DHW Storage tank (150 L)
		Profile 4 17h-18h 100%		System D 10 x DHW Storage tank (115 L - T2) 10 x DHW Storage tank (190 L - T4)

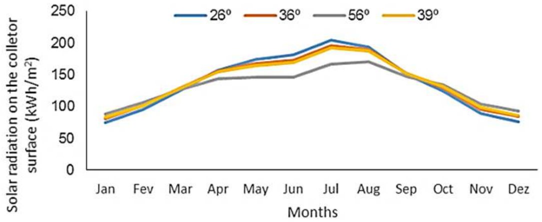

Fig. 3. Solar radiation for different collector inclinations

The results of the Solterm simulation are shown in Table 3 for each of the tested inclinations.

Table 2
Results of the collector inclination simulation

Angle	Wasted Energy [kWh]	Provided Energy [kWh]	Auxiliary Energy [kWh]	Total Energy [kWh]	Solar Fraction [%]
26º	6539	39933	8931	48864	81,7%
36º	5454	40272	8593	48864	82,4%
56º	1589	39381	9483	48864	80,6%
39º	**4879**	**40287**	**8577**	**48864**	**82,4%**

It can be concluded that:

- The month where the inclined radiation is highest for the inclinations of 22º, 39º and 36º is July, whereas the inclination of 56º has the highest radiation in August.
- The heating needs are inversely proportional to the inclined radiation. In other words, in the summer months, the demand value for charge is lower and in winter months the demand is 15% higher.
- In terms of solar fraction, there is little significant difference (0.7%) between the theoretical inclination for summer (26º) and the optimized inclination given by the program (36º). Therefore, the deviations in inclination will not harm the systems. The optimisation determined by the program, 39º, has a solar fraction of around 82.4%, and therefore it will be used in the next simulations described in this dissertation.

3.1.3. Simulation 2 – Demand Profile

Information about thermal load or consumption is very important to analyse the performance of solar thermal systems. The variable does not refer to the system itself but to its future use in uncontrolled conditions. As with the specification of the solar resource, the definition of consumption is a source of uncertainty in estimating the system's performance.

In this study, the parameters in Table 1 were fixed. Regarding the collectors, the Vulcano FKT 2S is unchanged and the inclination is now established at 39º (determined in Simulation 1). As far as the rest of the parameters go, they are the same as those used in the previous simulation.

To better understand the influence of the demand profile on the performance of a solar thermal system, four different demand profiles were studied. The demand profiles considered for this investigation are presented in Fig. 4. Demand profile 1 is characterised by a 70% consumption in the morning and a 30% consumption in the afternoon and demand profile 2 is the opposite. Demand profile 3 is characterised by a uniform distribution of the consumption throughout the day. All the consumption in demand profile 4 is between 17h and 18h. The most constraining profile will be used in future simulations.

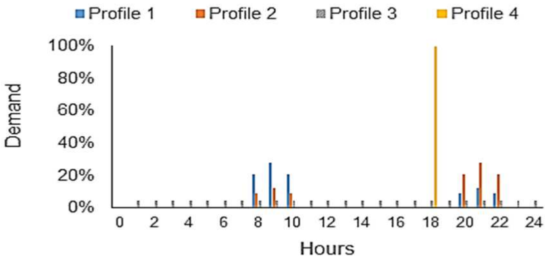

Fig. 4. Demand profiles over the day

The results shown in Table 3 represent the influence of the demand profile on the efficiency of the solar thermal system.

Table 3
Results of the demand profile simulation

Demand Profile	Wasted Energy [kWh]	Provided Energy [kWh]	Auxiliary Energy [kWh]	Total Energy [kWh]	Solar Fraction [%]
Profile 1	**4192**	**3887**	**9978**	**48864**	**79,6%**
Profile 2	4564	38927	9937	48864	79,7%
Profile 3	246	39420	9444	48864	80,7%
Profile 4	4944	40271	8594	48864	82,4%

It can be seen that:

- The results for profiles 1 and 2, which are the closest to real housing fractions, lead to lower solar fraction figures and therefore require the most energy. These profiles have two critical timelines in DHW consumption, in the morning and at night.
- Profile 3 can be used in an industrial unit with an equal amount of warm water every hour, for example. This profile is the one that generates least waste in terms of retrieved energy. However, its solar fraction is still lower than profile 4.
- The fourth profile shows the best solar fraction since the demand is in the afternoon, after the solar exposure. Therefore, this profile has the highest values of wasted energy.

It is important to mention that the 4 demand profiles, despite being different, only show deviations in the solar fraction of around 2.8%.

As profile 1 is the most constraining, it was the one used in the next simulations.

3.1.4. Simulation 3 – Type of Collector

The choice of the solar collector is very important to the behaviour of a solar thermal system. To study this effect, three different collectors were chosen: i) unglazed collector; ii) flat-plate collector, and iii) evacuated tube collector with the characteristics shown in Table 5.

As in the previous simulations, some parameters were fixed. In this case, the smallest number of collectors needed to obtain a 70% minimum overall solar fraction was calculated.

Table 4
Solar collector properties

Specifications	Unglazed collector	Flat-plate collector	Evacuated tube collector
Manufacturer	FAFCO	Vulcano	Buderus
Model	Sonnenkollektor 3.0 m^2	PremiumSun FKT – 2S	Logasol SKR 12.1R
Optical efficiency	0.887	0.794	0.640
Thermal loss a_1 [W/m^2.ºC]	12.580*	3.863	0.075
Thermal loss a_2 [W/m^2.ºC^2]	0.044	0.013	0.005
Collection Area [m^2]	2.978	2.430	2.570

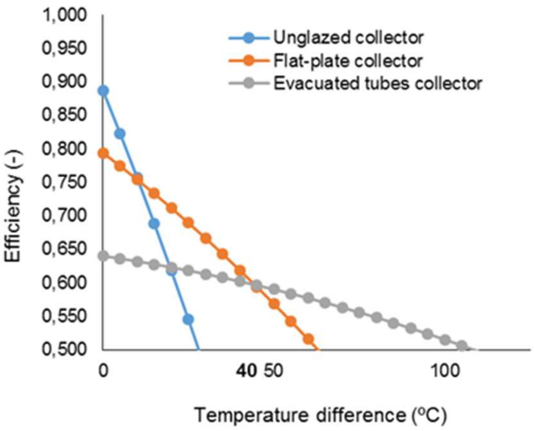

Fig. 5. Collector efficiency curves

The fixed parameters were the inclination and the demand profiles, already analysed and determined. The system type and the storage tank are the same as in the previous simulations (Table 1).

Table 5
Results of the collector type simulation

Collector Type	Unglazed collector	**Flat-plate collector**	Evacuated tubes collector
Solar Fraction [%]	70.2%	**70.8%**	71.5%
Productivity [kWh/m^2]	295	**620**	800
Overall system performance [%]	18%	**37%**	48%
Collector Area [m^2]	116.22 (39 modules)	**55.80** **(23 modules)**	43.69 (17 modules)
Efficiency for ΔT=35ºC	0.393	**0.643**	0.631

The influence of the collector was studied by combining two analyses, a theoretical one, based on the efficiency curve of each collector, constructed according to its manufacturers' specifications and an empirical analysis through the performed simulations.
Fig. 5 presents the efficiency curves of the three collectors. They were calculated with an irradiance of 1000 W/m^2 and with the values given in Table 4. The results are shown in Table 5.
From Fig. 5 it can be seen that until a 10 degree temperature difference, the unglazed collector has a better efficiency. Above that difference, the flat-plate collector has the highest efficiency. The evacuated tube collector only has the highest efficiency when the temperature difference is above 35 degrees.
The unglazed collector is not suitable when there is such a temperature difference given the fact that its efficiency is below 40% and the yield is below 20%. Hence, an area of more than 100 m^2 would be needed, which is more suitable for swimming pools.
The decision would be between the flat-plate and the evacuated tube collectors. The theoretical values show that the first have an efficiency of 0.643, better than the second with only 0.631. Regarding the productivity parameters, annual performance, area required and module number, we could choose the evacuated tube collector since its parameters are higher. Nevertheless, its price per square meter is twice that of the flat-plate collector. It was therefore decided to use them instead.

3.1.5. Simulation 4 – Storage type

At this stage, the decisions about which collector to use, its inclination and the demand profiles have already been made. The influence of the storage method, which varies according to the type of system, is studied next.

- System A – Centralised solar collection, water storage and auxiliary heating system;
- System B – Centralised solar collection and water storage and individualised auxiliary heating system;
- System C – Centralised solar collection, individualised water storage and auxiliary heating system;
- System D – Individualised solar collection, water storage and auxiliary heating system.
  - System D1 – individualised collection and storage for all T2 apartments.
  - System D2 – individualised collection and storage for all T4 apartments.

As with the last series of simulations (Simulation 3), the smallest number of collectors were varied until a 70% minimum fraction was obtained in each system, so that the results could be compared and analysed.
It should be noted that system D was split into two subsystems, one for T2 units and the other for T4 units.

Table 6
Type of storage and heat exchanger systems

Specifications	System A	System B	System C	System D1 (x10)	System D2 (x10)
Storage tank					
Manufacturer	Buderus	Buderus	Buderus	Buderus	Buderus
Model	CV-M1	G-I	Logalux ER – 160	Logalux ER –120	Logalux ER – 200
Type	DHW	Inertia	DHW	DHW	DHW
Volume	1500 L	1500 L	150 L	115 L	190 L
Quantity	2	2	20	1	1
Diameter	1160 mm	1160 mm	540 mm	540 mm	540 mm
Height	2320 mm	2320 mm	1172 mm	922 mm	1432 mm
Material	Glazed metal	Stainless steel	Glazed metal	Glazed metal	Glazed metal
Global Thermal loss coefficient	9.3 W/K	8.8 W/K	2.2 W/K	1.9 W/K	2.5 W/K
Heat exchanger					
Type	Internal	External	Internal	Internal s	Internal
Efficiency	55%	75%	55%	55%	55%

These systems make up the total of all the individual systems.

Furthermore, in system D it was not possible to obtain results with a 70% solar fraction since using fewer collectors would lower the result.

Table 7
Results of the storage type simulation

Specifications	System A	**System B**	System C	System D
Solar Fraction [%]	70.8%	**70.6%**	70.7%	78.3%
Productivity [kWh/m^2]	620	**678**	527	394
Global system performance [%]	37%	**41%**	32%	24%
Collector Area [m^2]	55.80 (23 modules)	**50.95 (21 modules)**	65.50 (27 modules)	97.00 (40 modules)
Wasted Energy [kWh]	415	**15**	701	6330
Provided Energy [kWh]	34610	**34519**	34546	38250
Auxiliary Energy [kWh]	14255	**14346**	14318	10610
Total Energy [kWh]	48864	**48864**	48864	48860

From Table 8 it can be concluded that:

- The centralised systems (A, B and C) have, in general, more interesting results than the individualised system (D):
  - o Productivity (500 kWh/m^2) higher than the centralised systems (394 kWh/m^2)
  - o Global system performance higher than 30%, whereas the individualised systems had an annual yield of 24%.
- Of the centralised systems, it appears that System C has the lowest results, due to the fact that the sum of the thermal losses inside the storage tanks, in each unit, is higher than the sum of the losses in the two 1500 L storage tanks.
- Comparing systems A and B, both with 1500 L storage tanks, it is possible to see that the inertia one has better results because of the exchanger efficiency (75% vs. 55%), compared with the DHW storage tank. Another factor is the lower thermal losses coefficient in the storage tank (8.8 vs 9.3).
- System B has nearly zero wasted energy, which suggests a very effective use of the endogenous source.

A test according to Portuguese legislation [27] was also carried out. All the systems meet the regulatory requirements.

3.1.6. Sensitivity analysis

At this stage, by which system B has been found to be the best system, it is relevant to analyse its sensitivity to its catchment area and its storage capacity. In other words, by varying these factors we can evaluate their influence on some indicators, particularly the solar fraction, productivity and efficiency.

3.1.6.1. Collector area

The collector chosen for the base system was the Vulcano PremiumSun FKT-2S. For this sensitivity analysis, the number of collectors was changed from 21 to 16, 26, 31 and 36.

Table 8 shows that a rise in the collecting area leads to a significant improvement in the system's solar fraction.

Table 8
Collector area influence on System B

Features	16 collectors 38.82 m^2	21 collectors 50.95 m^2	26 collectors 63.08 m^2	31 collectors 75.21 m^2	36 collectors 87.34 m^2
Solar Fraction [%]	61,4%	70,6%	76,4%	80,3%	83,2%
Productivity [kWh/m^2]	773	678	592	522	466
Overall system performance [%]	47%	41%	36%	32%	28%
Wasted Energy [kWh]	0	15	296	1164	2603
Provided Energy [kWh]	29991	34520	37347	39263	40657
Auxiliary Energy [kWh]	18873	14344	11517	9602	8207
Total Energy [kWh]	48864	48864	48864	48864	48864

The greater the number of modules, the greater the solar fraction. But this influence declines as the number of modules rises, as shown in Table 8, where the number of modules increases from 31 to 36 but the rise of the solar fraction is less than 3%.

Table 9
Storage tank specifications

Specifications	Inertia storage tank G-I 1500 L	Inertia storage tank MV-3000-I	Inertia storage tank MV-4000-I	Inertia storage tank MV-5000-I
Storage tank				
Manufacturer	Buderus	Lapesa	Lapesa	Lapesa
Model	G-I 1500	MV-3000-I	MV-4000-I	MV-5000-I
Type	Inertia	Inertia	Inertia	Inertia
Volume	1500 L	3000 L	4000 L	5000 L
Quantity	1	1	1	1
Diameter	1160 mm	1660 mm	1910 mm	1910 mm
Height	2320 mm	2305 mm	2310 mm	2710 mm
Insulation thickness	6.0 cm	8.0 cm	8.0 cm	8.0 cm
External area	8.76 m^2	14.04 m^2	16.85 m^2	19.12 m^2
Heat exchanger				
Type	External	External	External	External
Efficiency	75%	75%	75%	75%
Thermal losses coefficient				
Global	8.8 W/K	14.0 W/K	16.9 W/K	19.1 W/K
Specific	1.0 W/m^2/K	1.0 W/m^2/K	1.0 W/m^2/K	1.0 W/m^2/K

The sensitivity analysis on the storage capacity of the thermal solar system involved first altering the number of storage tanks. Next, simulations were performed for tanks of different volumes.

It is important to perform these two tests to understand the effect of thermal loss for various tanks versus one tank of fixed capacity.

In Table 9 we can see the characteristics of the tanks considered.

Simulations were conducted with 1, 2, 3 and 4 tanks with 1500 litre capacity. The results are shown in Table 10.

Table 10
Storage volume sensitivity in system B, with 1500 litre tank

Storage volume (l)	1500 (1 tank)	3000 (2 tanks)	4500 (3 tanks)	6000 (4 tanks)
Solar Fraction [%]	65.3%	70.6%	71.2%	70.7%
Productivity [kWh/m^2]	626	678	683	678
Overall system performance [%]	38%	41%	41%	41%
Wasted Energy [kWh]	647	15	0	0
Provided Energy [kWh]	31906	34520	34792	34528
Auxiliary Energy [kWh]	16958	14344	14072	14336
Total Energy [kWh]	48864	48864	48864	48864

- As expected, between having one and three tanks there is an improvement in all the results, such as an increase in the solar fraction, higher productivity, more energy supplied, less energy wasted and less back-up energy needed.
- However, with four tanks, there is an unusual situation given that the indicators show less favourable results than for three, there bein an inflection point (Fig. 6).

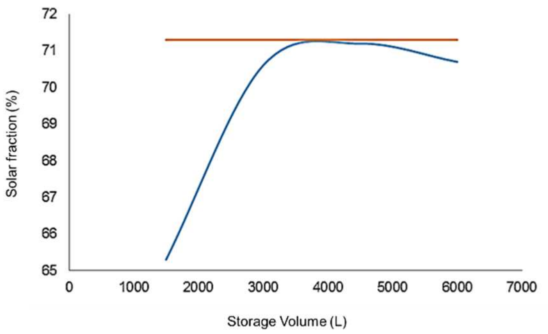

Fig. 6. Solar fraction evolution with storage volume in 1500 L tank simulations

- One reason for this may be that the 21 solar collectors do not have enough capacity to heat the liquid in the four tanks at the same time. In fact, the smart management of the use of the tanks would be a possible strategy. In other words, the successive use of the tanks would only be activated if necessary, thereby avoiding wasting energy and warming up all the tanks at the same time. The level of detail of Solterm does not allow this option to be tried for this system, however, other programs such as TRNSYS do offer this feature.

Simulations were conducted with the four different tanks and the results are shown in Table 11.

Table 11
Storage volume influence on system B, with different capacity tanks

Storage volume (l)	1500	3000	4000	5000
Solar Fraction [%]	65.3%	71.3%	72.4%	72.9%
Productivity [kWh/m^2]	626	684	694	699
Overall system performance [%]	38%	41%	42%	42%
Wasted Energy [kWh]	647	27	0	0
Provided Energy [kWh]	31906	34862	35377	35608
Auxiliary Energy [kWh]	16958	14003	13488	13257
Total Energy [kWh]	48864	48864	48864	48864

- The results obtained in this simulation show a favourable evolution in the indicators of the systems, where volume growth causes a successively smaller evolution, similar to the collection area.
- It is important to note there is no inflection point, just like the first series of simulations.
- After the daily consumption volume is reached in the tank, the changes in the indicators are not very significant, unlike what happens in the catchment area, which has a notable influence on the system output.

3.2. EnergyPlus

In study B, EnergyPlus was used to compare with the results in the previous study, particularly those related to System D1 (Table 12), a T2 apartment, through a dynamic simulation conducted under the local conditions of the case study (Porto).

The energy simulation conducted in this study could be divided into three steps, one being the introduction of data for the development of the module, the second being the simulations and the last one being the analysis of the results. Since this process is iterative, the results contributed to the definition of the optimised system.

The modelled system is explained schematically in Fig. 7. First, it is composed of an array of solar collectors that are connected to a storage tank via a pump. This tank is connected to an auxiliary one that has a resistor to heat the water, when necessary. In the middle there is a 3-way valve that can let cold water in, to be combined with water from the storage tank to avoid taps' burns.

This requirement is due to the fact that the water temperature in the storage tank was 82ºC in order to make the most of the solar energy.

Table 12
System D1 Specifications

Specifications	System D1
Collector	
Manufacturer	Vulcano
Model	FKT 2S
Quantity	2
Collector area	4.85 m^2
Azimuth	South
Storage tank	
Manufacturer	Buderus
Model	Logalux ER – Model 160
Quantity	2
Total volume	115 L
Heat exchanger	Internal
Effectiveness	55%
Demand profile	
Profile 1	Morning 70%, Afternoon 30% 120 L/day

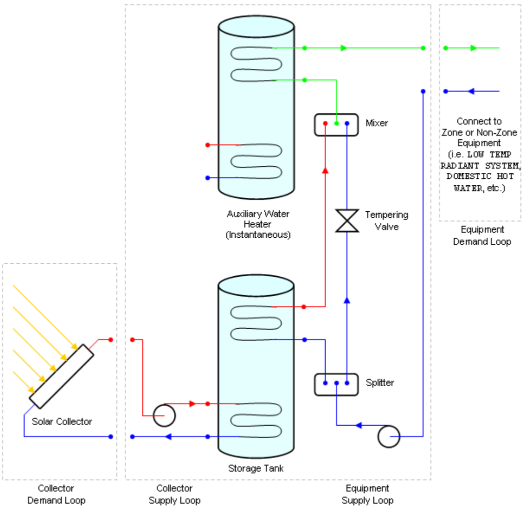

Fig. 7. System connections diagram

In this work, two weather files were used, one relating to the location of Porto, taken from the EnergyPlus [28] website, designated as *predefined*, and the other the same as the first but with the data on temperature, daily total solar radiation and hourly diffuse solar radiation contained version 5.1.4 of the Solterm program, designated as *custom*.

3.2.1. Output reporting

The analysis of the results of the simulations – outputs – makes it possible to evaluate the behaviour of the solar thermal system adopted.

As the fields are being filled out through IDF Editor, the variables in the Output: Variable Dictionary menu are being inserted. However, not all of the variables will be used in this paper. Those used are:

- Environment:Site Outdoor Air Drybulb Temperature
- Environment:Site Solar Altitude Angle
- Collector Surface 1:Surface Outside Face Incident Solar Radiation Rate per Area
- Sinks:Water Use Equipment Hot Water Mass Flow Rate
- Collector 1:Solar Collector Heat Transfer Rate

The first three points are related to the climatic data and not directly to the parameters calculated by the simulation – they support the conclusions related to the two climate files used.

The variable *Sinks:Water Use Equipment Hot Water Mass Flow Rate* concerns consumption and it is important to evaluate it since it is intended to compare results of the DHW consumption given by Solterm and EnergyPlus (chapter 3.1).

Finally, the variable *Collector 1: Solar Collector Heat Transfer Rate* is the energy provided by the solar collector to the thermal solar system.

3.2.2. Comparison between the results of EnergyPlus and Solterm

In this sub-section, the results obtained in EnergyPlus and in Solterm are compared, considering that the intention was to simulate in EnergyPlus a system very close to the one in Solterm. Hence, the comparison of the results is essential.

The first simulations were aimed at introducing the characteristics of the system, such as the simulation configurations, solar collectors, tanks and consumption, with the first valid results being used to confirm these consumptions through the variable *Water Use Equipment Hot Water Mass Flow Rate.*

After the introduction and validation of the consumption, the provided energy verifications were followed by the system.

The first simulations with the defined and validated system were conducted with the weather file predefined for Porto, as mentioned.

Fig. 8 shows the results with the predefined climate file from EnergyPlus and Solterm.

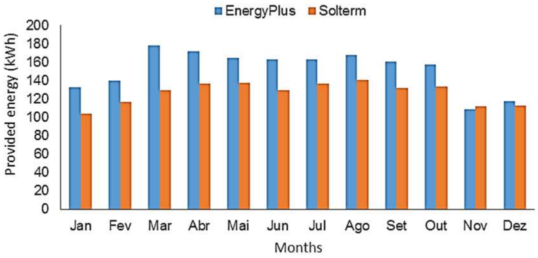

Fig. 8. Energy provided over the year using EnergyPlus default weather file and Solterm

The total energy values calculated by EnergyPlus have are 16% higher than the ones calculated by Solterm.

It can be seen that there are some months where the EnergyPlus values are not those expected, particularly in March and April, which are the highest of the year. The Solterm results show an almost natural evolution from January (winter) to August (summer), followed by a decrease. These unpredicted values could arise from the information in the climate file, particularly the incident radiation and the exterior temperature.

After these observations, it was decided to enter the climatic data from version 5.1.4 of Solterm in the EnergyPlus climate file.

Temperatures and total horizontal radiation in the predefined weather file and Solterm are shown in Fig. 9 and Fig. 10.

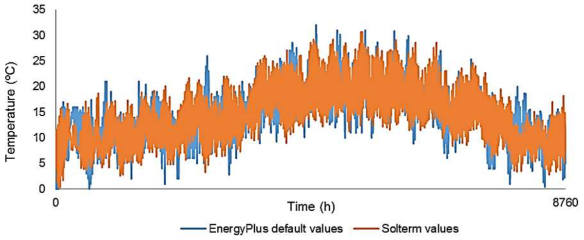

Fig. 9. Temperature comparison between EnergyPlus default values and Solterm values

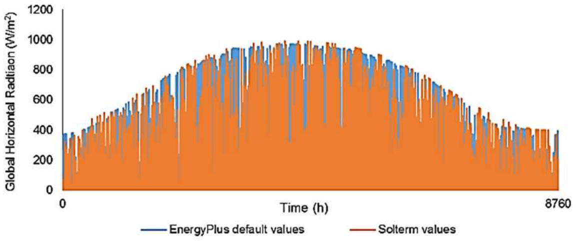

Fig. 10. Total horizontal radiation comparison between EnergyPlus default values and Solterm values

Table 13
Summary of average EnergyPlus default values and Solterm values

Average values	EnergyPlus	Solterm	Difference
Temperature [ºC]	14.32	14.03	2%
Totaç Horizontal Radiation [W/m^2]	178.84	165.45	7%

In fact, the difference between them is not very significant. Nevertheless, the use of a single custom climate file, with Solterm data, could lead to a smaller difference.

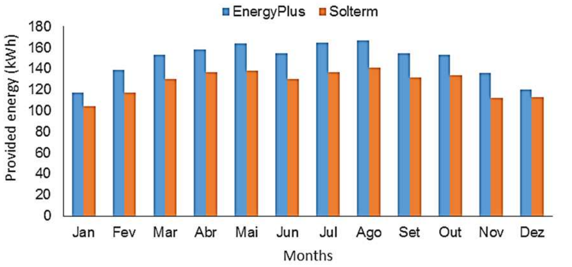

Fig. 11. Energy provided over the year using EnergyPlus customised weather file and Solterm

Analysing Fig. 11:

- The unexpected values in March and April do not appear in this simulation, which suggests that they were related to the parameters of the climate file. In this group of results, it is possible to see an increase in the provided energy until August and a regression afterwards.
- Comparison with the Solterm values showed an average difference of 14%, which may be related to the way each program works. The way the entry of data (detail) is processed and the calculation methodology of each program could have determined this difference.

3.3. Financial analysis

Besides being compulsory, the implementation of a solar thermal system has considerable energy, economic and environmental advantages. The different costs associated with each system and the savings that they generate compared with a conventional DHW system are evaluated and compared next.

For the financial analysis, the next indicators were considered the present net value, payback period and internal rate of return.

In study C it was decided to implement two approaches, one considering the prices without value added tax (VAT) and the value of the simple electricity tariff, and the other considering the prices including VAT and the real value of electricity and other relevant taxes.

3.3.1. System costs

The cost of a thermal solar system can be divided into the installation cost and operating costs, which are the sum of the maintenance costs and the running costs.

Because of its components, each system has an installation value. A national company with projects related to renewable energies [29] was able to supply the figures for the installation costs and these are displayed in Table 14.

It is important to note that system D considers the sum of the values of the 10 D1 systems and the 10 D2 systems. In other words, the cost of 20 contracts to install 20 separate systems. Nevertheless, in reality, since it is the developer/constructor of the building who is in charge of the installation, it should be considered as only one contract, with a lower value thanks to an associated discount of 20% [29]. This discount was applied to System D’ in order to understand the real value of its installation.

Table 14
System installation cost

Systems	**Number of collectors**	**Total System Cost (€)**
System A	23	33,785.00
System B	21	37,347.00
System C	27	49,494.00
System D	40	72,690.00
System D’	40	58,152.00

The operating costs could be divided into maintenance costs and running costs.

Table 15
System maintenance costs

System	**Total Cost (€)**
System A	1,013.55 €
System B	1,120.41 €
System C	1,484.82 €
System D	2,180.70 €
System D’	1,744.56 €

The maintenance costs of each system were estimated as 3% of the original installation cost [12]. The resulting figures are presented in Table 15.

The running costs considered two types of energy:

- Energy used in the auxiliary heating system
- Energy used in hydraulic system.

The energy provided to the auxiliary heating system was calculated in sub-section 3.1.5 of this article, and it is added to the energy provided by the STS and thereby covers all the DHW needs.

Regarding the hydraulic system energy, the same value was assumed for all the systems in order to simplify the calculations. After contacting local companies [29, 30], a figure of 400 W of maximum power was estimated for the hydraulic group (primary + secondary). An average use profile of 6 hours per day, 365 days per year, was estimated, making a total of 876 kWh.

Table 16
System operating costs

System	Auxiliary heating system [kWh]	Hydraulic system [kWh]	Energy Consumption [kWh]	Total Cost [€}
System A	14,255	876	15,131	2,422.47
System B	14,346	876	15,222	2,437.04
System C	14,318	876	15,194	2,432.56
System D	10,610	876	11,486	1,838.91
System D’	10,610	876	11,486	1,838.91

As far as the energy costs are concerned, a value of 0.1601 €/kWh was assumed, which tallies with the electricity price in Portugal [31].

Table 16 gives the values obtained for annual running costs.

- Despite being the most energetically efficient, System B has a higher installation cost than system A because of the value of the transfer stations in each apartment.
- As expected, systems D and D’ have the most expensive installation cost. Still, the discount offered by the supplier for system D’ made it very similar to system C.
- The running costs of the systems are less important parameters for two reasons. The first is the value of the back-up system, which is much the same in all of the systems (a 70% fraction was considered), except System D, for the reasons stated in 3.1.5. The second reason is that the value for the hydraulic system was fixed in order to simplify the calculations. Therefore, it is important to understand that there are running costs associated with each system, but comparing them does not have much meaning, given the assumptions made.

3.3.2. Net present value

The net present value (NPV) is an indicator used to evaluate the profitability of investment projects. NPV is the sum of all cash-flows (CF_k) over a period of time for a certain project. Its value has been updated each year using a discount rate (i).

It can be calculated through the following formula:

$$NPV = \sum_{k=0}^{n} \frac{CF_k}{(1+i)^k} \qquad (1)$$

NPV is used to determine the profitability of an investment in the long run, taking into account the initial investment and whether the result is positive or not, whether the project is profitable or not.

In this case, the cost of a conventional system for heating sanitary water was calculated (with back-up system – electricity). This figure was then compared with the cost presented above for each system. Hence, each cash-flow (CF_k) is the amount saved annually by a certain system compared with a conventional system. In other words, it is the difference between the total energy cost of a conventional system (CTE_{SC}) and the total cost of a solar thermal system (CT_{SST}).

$$CF_k = CTE_{SC} - CT_{SST} \qquad (2)$$

In terms of the refresh rate, it was considered that Portugal in 2015 had a risk-free rate [32] of 3.10%.

In relation to the life span, the value that the main manufacturers estimated for solar thermal systems was assumed: 20 years [29, 30].

The costs were updated in each of the years of the calculations through the following formula, where the initial cost is given by C_i and the inflation rate was ψ.

$$C_n = C_i(1+\psi)^n \qquad (3)$$

Two different inflation rates were used to calculate this indicator, one general inflation rate, used for maintenance costs, and another for electricity.

The general inflation rate used was the rate expected by Banco de Portugal in its economic newsletter of December 2014 [33], 0.7%. Meanwhile, the electricity inflation rate considered was the one monitored between 2014 and 2015, 3.30% [31, 34].

The NPV values are presented in Table 17.

Although it is possible at a technical level to collect more energy with System B (sub-section 3.15), with only 21 collectors, System A has a higher economic profitability because it is not necessary to install transfer stations in fractions, so the installation cost is lower.

3.3.3. Payback time

The payback time is calculated using the initial investment and the earnings over the lifespan of the system, for a certain interest rate. This analysis again considered that Portugal had a risk-free rate of 3.10% in 2015. Thus, the payback time (PB) is calculated as the sum of the last year in which NPV is negative (p), the quotient between the combined cash-flows for that year (CFA_p) and the difference between the combined cash-flows for that year and the following year (CFA_{p+1}).

$$PB = p + \frac{CFA_p}{CFA_p - CF_{Ap+1}} \qquad (4)$$

Looking at Table 17 it is possible to see that the payback times calculated are slightly higher than expected (5, 6 years).

3.3.4. Internal return rate

The internal return rate (IRR) represents the maximum rate of return of the project. In other words, it is the discount rate which, at the end of the lifespan of the project, brings the NPV to zero. IRR is the maximum interest rate that can be applied to an investment such that NPV=0 .

$$\sum_{k=0}^{n} \frac{CF_k}{(1+IRR)^k} = 0 \qquad (5)$$

Since this equation is mathematically difficult, it was solved by using successive approximations in Microsoft Excel.

As expected (Table 17), Systems A and B have the highest IRR: It is important to note that the 5% value for System D is quite a low rate. In fact, it is very close to the considered discount rate, which makes the payback period of the investment also come close to the lifespan of the project.

3.3.5. Results analysis

The results are summarised in Table 17.

When it comes to the thermal solar systems, the results are not so interesting.

Even though it is possible to repay the investment within the lifespan of the system, it was expected that all of the systems could be paid in half of the lifespan.

Table 17
Financial indicators resume with energy cost of 0,1601 €/kWh

System	NPV (€)	PB	IRR
System A	60,479.45	7.86 years	16%
System B	54,935.70	8.43 years	14%
System C	37,136.23	11.85 years	9%
System D	15,089.36	16.86 years	5%
System D’	36,501.96	12.71 years	8%

After contacting several companies [35, 29, 30], it was possible to see that the standard payback period for these systems is between 5 and 10 years, depending on the investment amount and equipment used.

Table 18
Calculation of real energy cost

Parameter	Qt.	Unit cost	VAT	Total cost (€)
Active power [kWh]	250	0.1601	23%	49.23
Contracted power (20.7 kVA) [-]	1	24.3110	23%	30.48
Tax on electricity consumption [kWh]	250	0.0010	23%	0.31
Portuguese Energy and Geology Department tax [-]	1	0.3500	23%	0.43
Audiovisual contribution [e.g.]	1	2.6500	6%	2.81
			Total	83,26
		Final cost per kWh		**0.34**

To obtain results more appropriate to Portugal, the real price of electricity was chosen, with all the fees and increments included. The value of VAT was also considered in the installation, maintenance and operating costs.

To calculate the real value of each kWh, a T4 apartment was taken as a case study, where the monthly consumption reaches 250 kWh. By taking the electricity bills in Portugal [July 2015] and consulting the sites of energy companies [31, 34], it was possible to achieve the results shown in Table 18.

The value considered previously – 0.1601 €/kWh – is low less than half than the real value that each consumer pays, € 0.34.

The results of the indicators are shown in Table 19.

Table 19
Summary of financial indicators for energy cost of 0.34 €/kWh

System	NPV (€)	PB	IRR
System A	169,659.08	4.08 years	28%
System B	162,583.26	4.57 years	25%
System C	140,769.00	6.28 years	19%
System D	124,123.55	9.65 years	13%
System D’	150,461.05	7.71 years	18%

Table 19 shows that the payback time is around 4 to 10 years, which is closer than the expected values. Moreover, IRR is between 13 and 28%.

It is interesting to see that System D’, besides having a lower internal rate of return than System C, ends up having a higher net present value. This means that assuming the same refresh rate, the benefits in the final life span, when updated to the current time of system D’, are better than System C’s benefits.

As it is possible to see in the installation cost of systems D and D’ that the installation of a collective system in one contract is economically more favourable than installing them individually.

It should be noted that if all the costs related to the energy bill are considered, the real value per kWh is considerably higher than the tariff price of consumption.

The profitability of solar thermal systems is currently very interesting, with a payback time of 4 years for System A, located in one of the less favourable areas of the country (Porto), even without additional subsidies. The annual figures for horizontal radiation in Porto are estimated to be 1446 kWh/m^2. Still, it is possible to obtain a solar fraction of 70.8% with system A.

Regarding other parts of the country, such as Lisbon or Faro, with horizontal radiation of 1646 kWh/m^2 and 1729 kWh/m^2 respectively, it is possible to achieve a solar fraction of 82.2% and 85.5% and, consequently, payback periods of 3.51 and 3.38. Other locations are shown in Table 20.

4. Conclusions

The goal of this paper was the analysis of the impact of solar thermal systems with different configurations in multifamily buildings. In order to obtain an energy optimisation of the system, several parameters were analysed, such as the collector inclination, the demand profile, the type of collector and the type of storage. Solterm software was used.

Regarding the collector inclination, for the location of the case study (Porto – latitude: 41, long. 16^o N), it was found that the most favourable inclination to maximize

Table 20
Values for other Portugal's cities

City	Horizontal Radiation [kWh/m^2]	Direct normal Radiation [kWh/m^2]	Provided energy [kWh]	Total energy [kWh]	Solar fration [%]	Payback time [years]
Porto	1447	1655	34612	48864	70.8%	4.08
Lisboa	1646	1869	37624	45757	82.2%	3.51
Faro	1729	1939	37875	44311	85.5%	3.38
Castelo Branco	1621	1857	38116	48006	79.4%	3.64
Funchal	1394	1474	31814	44792	71.0%	4.07
Ponta Delgada	1361	1498	32129	45860	70.1%	4.13

the provided energy is 39º. Nonetheless, the results for the other studied inclinations were not much worse, only about 2% in terms of provided energy.

Another parameter studied was the demand profile. Four profiles were analysed. The first has the highest demands and has a consumption of 70% in the morning and 30% in the afternoon. It was found that the profile with the most uniform distribution of consumption throughout the day is the one that generates least energy waste; however, it is far from the typical housing reality.

Next, three types of collectors were studied. The results show that in a housing context, where the water temperature increase is 35ºC (50-15 ºC), it would be best to choose the glass-covered flat-plate collector. The collector with vacuum tubes has higher productivity and yield than the other systems. However, it costs almost twice as much per square meter, and occupies a smaller area.

In the subsequent simulations, many types of storage that lead to centralised systems (A, B and C) were investigated. These results were more interesting than those of the individualised system, D. In terms of productivity, the centralised systems gave results higher than 500 kWh/m^2, whereas the figure for individualised ones was 394 kWh/m^2. Regarding annual income, the centralised systems offer a percentage of 30% compared with 24% for the individualised ones.

In the group of centralised systems, it was confirmed that system C has the poorest performance since the sum of the thermal losses from the tank in each aparment is higher than the sum of the losses from the two 1500 L tanks (Systems A and B).

Next, Systems A and B were compared, both with 1500 L tanks, and it was seen that with the inertia one (B) it was possible to obtain identical results to A with a small catchment area due to the exchanger efficiency (B – 75% vs. A-55%) and to the lower thermal loss coefficient, when compared to A's DHW tank.

System B almost has no wasted energy, and therefore it is the system that takes best advantage of the endogenous source.

Solterm was used to perform a sensitivity analysis of the system with best energy results (system B), catchment area and storage volume. In general, an increase in the catchment area and storage volume improve the performance of the system. However, the influence decreases as the area and volume increase.

In the section on the EnergyPlus program, a comparison was made between the results from Solterm and EnergyPlus. After several simulations and changes in configurations and parameters of the model, a 14% difference between the obtained results was reached with respect to the energy provided to the solar thermal system. The reasons for this disparity in the results may be related to the information each program can receive and to the methodology used in the calculations. Solterm is a more straightforward program, with fewer instructions and less parameterization, where the performance of a solar system is analysed through an energy simulation with almost stationary conditions. In other words, the energy balances are simulated every 5 minutes, where the weather and system conditions are considered constant. However, EnergyPlus conducts a dynamic simulation, where the thermal charges in the catchment areas, the air and ventilation treatment system and the thermal power generation plants are calculated simultaneously and their interaction is relevant. The calculation method is fundamental to EnergyPlus, which is based on the energy balance, in which the air temperature inside is considered uniform.

Section 3.3, presented the different costs associated with each system and some indicators were calculated. It could be seen that System A has the lowest installation costs, since it has the smallest number of components. Despite being the system that takes the best advantage of solar energy, which results in a smaller catchment area (21 collectors – B vs. 23 collectors A), System B ends up with an installation cost higher than A owing to the transfer stations in each unit. It is important to mention that System D may cost less if it is installed under one contract, leading to system D', which is 20% cheaper.

Regarding the economic indicators, the use of VAT and other taxes applied by electricity companies has a great impact on the calculations of these projects. For example, the system with the best results, System A, has a payback period of 4.08 years when all items and taxes are considered (Energy cost=0.34 €/kWh). However, if they are not considered (Energy cost=0.16 €/kWh), the payback period may be as long as 8 years, The payback period is related to the location of the case study. If it were in Lisbon, the payback period would be 3.51 years and if it were in Faro, it would be 3.38 years.

Another interesting result is the fact that with centralised systems, planned from the very start, the payback period is longer than with individualised systems, meaning that they are a better solar resource relative to the initial investment. In this context, it would be useful for the designers to consider that Systems A and B are both interesting options in energy and economic terms.

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