Chapter

Holistic and Affordable Approach to Supporting the Sustainability of Family Houses in Cold Climates by Using Many Vacuum-Tube Solar Collectors and Small Water Tank to Provide the Sanitary Hot Water, Space Heating, Greenhouse, and Swimming Poole Heating Demands

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Abstract

This work presents a new proposal for supporting the sustainability of a single-family house in very cold climates by installing many vacuum-tube solar collectors and a small water tank in order to fulfill the whole dweller demands of heat: space heating, sanitary hot water, and warming both, a greenhouse (spring and autumn) and a swimming pool (summer). This way is obtained a sustained demand that maximizes the utilization of heat from solar collectors throughout the year. This system is designed intending to use the smallest tank that fulfills the winter heating demand, supported by vacuum-tube solar collectors and a little help from electrical heaters working just on the valley tariff. This innovative design gets the most sustainable (but affordable) solution. This goal can be achieved by using a small well-insulated overheated aboveground water tank, instead of the huge underground reservoir of heat used by most projects tested up today. These large communal projects use huge reservoirs to provide seasonal thermal storage (STES) capacity, but their costs are huge too. Besides, it was observed that all these huge STES suffer large heat losses (about 40%), due to constraints for thermally insulating such very heavy systems. On the contrary, our small aboveground water tank can be thermally insulated very well and gets affordable costs. In this work is developed dynamical solar-thermal modeling for studying this novel approach and are discussed its major differences with traditional design. This modeling is used to study the whole demands of heat for one family living in the same conditions of the Okotoks' project. The Okotoks' project is based on many flat solar collectors (2,290 m^2) and a huge (2,800 m^3) rocky-underground STES system in order to almost fulfill (97%) the space heating demand of 52 houses (15,795 kWh/y ea.) in Alberta (Canada), having an overall cost of 9 MU$ (173,000 U$ ea.). We have already shown in previous work that this new proposal could reach noticeably lower costs (€30,500) than the Okotoks' project in order to provide the same heating demand, by taking advantage of using 18 vacuum-tube collectors (solar area 37 m^2) and a small (72 m^3) well-insulated (heat losses 18%) water tank heated up to 85°C, which is the same temperature used in Okotoks and other traditional projects. Now, this proposal is enhanced by using a holistic approach to include other low-temperature demands (sanitary hot water and warming a greenhouse and swimming pool) that enhance the sustainability of dweller living. This way, the full production of heat from solar collectors is utilized (about six times larger than the single space heating demand, but using only 20 vacuum-tube solar collectors (21 m^2 solar area) and a very small (10m^3) water tank, reaching about a lower overall cost (€20,000), and so, the economic performance is enhanced as well. Besides, it is shown that using a small fraction of electrical heaters as a backup system (2%) and slightly overheating the water (up to 120°C@2 bar), which is feasible by using commercial stainless steel water tanks designed for such purposes, its economic performance could be again noticeably enhanced (reducing the overall cost to €20,000, and getting payback period less than two years). This way here is demonstrated the overall solar-STES system can be reduced by about half size meanwhile the energy output can be increased up to seven times. Hence, the thermal analysis performed suggested us strongly critic the traditional approach of using flat solar collectors instead of vacuum-tube collectors. This analysis shows that this choice has strongly driven the selection of a huge STES, which in turn increases noticeably the overall costs of the system since for such huge STES is mandatory to use underground reservoirs. However, this analysis also shows that without including those secondary demands, this proposal achieves a modest economic performance (payback period about 11 years) regarding its lower energy saved and compared against the "most smart" standard solution (one water tank with electrical heaters, costing about 5,000 U$ and exploiting the valley tariff of nocturnal electricity costing 0.1 €/kWh). On the contrary, when these secondary demands are included, the payback period is reduced by two years. Beyond the particular case studied here, this analysis suggests that the right design of any solar + STES system should be led by the solar production. On the contrary, the traditional design intends to fulfill one demand (space heating) concentrated during winter, and so, its performance is noticeably penalized, and the solution is definitely not to put a larger tank. Unfortunately, up today the poor performance of these projects has shown that this solar technology is (by far) unaffordable. Maybe its best days have gone, considering the enormous improvements achieved by another solar technology (using photovoltaic panels + heat pump + small daily-storage water tank), as it was discussed here.

Keywords: zero-energy buildings, seasonal thermal energy systems, solar collectors, household energy demand, thermal and economic analysis

1. Introduction

1.1 Previous works

In a previous work [1], we have already developed a dynamical thermal modeling of solar collectors linked to a seasonal thermal storage (STES) system. The major advantage of this model is its simplicity. This model uses one-step time and explicit numerical scheme so that it can be programmed easily on any standard spreadsheet, instead of other complex three-dimensional codes (like TRANSYS). Besides, in this work was deeply discussed that a complex code is completely unnecessary for modeling STES systems based on well-insulated water tanks. On the contrary, it was demonstrated by using physical simplifications that such systems can be modeled as a zero-dimensional system, and so, this simplest (the so-called lumped-capacity model) spatial modeling can be used, in which all the water tanks can be considered at the same homogeneous temperature. Furthermore, this work has also demonstrated that a very refined time simulation neither is necessary, since a large (seasonal) storage system would have only slow variations of temperature (cooled during winter and heated during summer) and so, the STES yearly evolution can be perfectly modeled by using one-day time step. Beyond these useful simplifications, the major strength of this simple model is to provide a useful framework for modeling the solar system (a set of solar collectors) together with the STES system, which in turn allows us to take-in-hand all the system parameters. These parameters comprise the solar collectors' parameters (their number, title angle, and their efficiency's equation), as well as the STES parameters (the water storage capacity, the insulation quality, and maximum/minimum working temperatures). Hence, the analysis performed has surprisingly shown that the behaviors of the STES and solar systems are actually coupled. This way, we have found that a small short-term STES working with many vacuum-tube solar collectors can provide the same overall performance (that is, to fulfill the space heating demand during winter) that a huge seasonal STES working with many flat solar collectors, meanwhile the first design reaches a noticeably lower cost.

In this work will be summarized the major findings obtained in this previous work [1] as the starting point for the present analysis. On this, it will be studying a novel proposal that could enhance the performance of this novel design. It uses an overheated water tank (up to 120°C) instead of the 85°C level previously used, which creates a slight overpressure (2 bar) that can be withstood by using commercial stainless steel tanks. Besides, this proposal follows a holistic approach in order to include all the secondary heat demands related to a family living in a very cold climate location, besides the space heating demand that is concentrated during winter. These demands comprise the sanitary hot water demand, warming a greenhouse (from spring to autumn), and swimming pool (during summer). Therefore, a sustained demand throughout the whole year is created. This is a key to maximizing the production of energy from solar collectors since the small STES only can provide a short-term (less than one month) storage capacity. This constraint was a serious drawback shown in the previous study, in which the surplus of solar energy produced by solar collectors must be avoided for ten months each year. Hence, we have realized that such kind of solar + STES system could be better utilized since it uses a very large number of solar collectors to fulfill the heating demand concentrated during winter, but its large potential for generating heat during the whole year is not exploited. Here was the starting point for the holistic approach (by including all the secondary demands of heat) studied here.

1.2 Present development of the (solar plus thermal storage) technology

During the last twenty-five years have been developed several testing projects of Seasonal Thermal Energy Store (STES) associated with a solar system based on many collectors for providing space heating to many houses (or department buildings) in cold locations, mostly in Canada and Germany [2, 3]. These projects have shown this technology is feasible, although very costly.

The first and most important project that will be considered here is the well-known Okotoks' project, developed by the Drake Lake Solar Community in this place (51°N) within the Alberta State of Canada. This project intends to create a sustainable solar community, and their performances are available online by internet, as well as by several technical reports. For example, Sibbitt et al. [4] has recorded their (solar and thermal) performances. This project works since 2007 up today, and it provides annually 97% of the space heating demand to 52 well-insulated houses (117 kWh/m^2/y and 135 m^2 ea., in this very cold climate (average 5.2°C and 5,020 heating degree days defined according to [5]). This project uses 798 flat solar collectors (2,290 m^2) and a long-term storage system that heats the underground rock by means of 144 very deep (40 m depth) wells drilled covering over a 700 m^2 field (that is, covering a 28.000 m^3 volume of rock). This huge STES system is designed to provide seasonal storage (that is, the solar collectors accumulate heat during summer, and houses demand heat during winter), but this design (using the rocky underground) only achieves an overall efficiency of 60%, since there are remarkable heat losses from the reservoir (heated up to 90°C) to the surrounding ground. This huge long-term STES system works together with another short-term system based on 240 m^3 water tanks, which provides the household space heating by using under-floor water systems. This is the right choice in order to maximize the thermal capacity of the reservoir (working within the usable 85–35°C range, instead of working within the usable 85–60°C range when hot-water radiators are selected as the heating system). The solar radiation received on the 45°-inclined collectors (13,902 GJ/y) is collected with an overall 31% efficiency, and can effectively store solar energy only during the warm season [6]. The heating demand in Okotoks is very concentrated during four months (94%), which is a typical characteristic of cold continental climates. These figures present an exigent scenario for a STES system that explains the superlative cost (U$173,000 per each house) of this project [7], mostly due to the extremely high cost of constructing the rock reservoir.

In previous work, we have already analyzed our novel approach for solving the heating demand of a single house on the Okotoks´ project. However, since this project uses a different kind of STES system, we need to state another two starting points for performing our study. For our purpose, just let us keep in mind the major parameters for every single house of the Okotoks' project: the cost (U$173,000 ea.), the solar collector area (44m^2), the rocky reservoir (538 m^3), and finally, the annual heating demand (15,795 kWh/y). These parameters will be useful for comparing after with other designs.

The second reference point considered here is the Friedrichshafen (48°N) project, working since 1996 in Germany for heating a department building. This project considered a STES system based on a huge (12,000 m^3 and 20 meters height) underground water tank. This tank is also very heavy since it is built by using 60 cm-thickness reinforced-concrete walls that include a 1.2 mm stainless steel liner. Although this STES system is huge, it can satisfy, only partially (just 25%), the space heating demand of a multifamily building (23,000 m^2, 100 kWh/m^2/y) by using hot-water radiators. The solar system comprises 4,050 m^2 flat solar collectors installed onto 38° inclined roofs [8, 9]. This project has preferred to use a huge water tank in order to reduce its area/volume ratio and so their specific heat losses and cost. This goal was achieved when it is compared against other similar (but smaller) German projects. So, this (12,000 m^3) tank achieves a lower specific cost (112 €/m^3) than the Hamburg project (4,500 m^3, 220 €/m^3) and the Hannover (2,750 m^3, 250 €/m^3) project [2]. However, due to its heavy mass and large depth, it is also very difficult to wrap this tank with standard isolative materials, which can withstand pressure up to 2 bars. So, the Friedrichshafen project has recognized heat losses of about 40% on this huge tank related to the lack of thermal insulation on its lower third (bottom and walls). Also by considering its heat losses of about 8% in the heat distribution system. This project shows the drawbacks of building a huge communal system, regarding our approach that designs a small system for each house. Besides, regarding the use of flat collectors working up to 90°C in cold climates, this project demonstrated that these collectors can achieve a poor average efficiency (30%). The total investment of this project (4 M€) is recognized by Bauer et al. [8] as a not cost-effective solution, regarding the low percentage (25%) of fossil fuel substituted. Let us note that by comparing the heat productions of the Friedrichshafen and Okotoks projects, the German project achieves an equivalent cost of about 128,000 dollars per Okotoks' house (considering an exchange conversion of 1.2 dollars per euro). So, even recognizing that the German solution is cheaper than Okotoks, it is not enough cheap to become an affordable solution by far. However, there are some interesting learned lessons obtained from these German projects; the feasibility of using water tanks as the main thermal storage system (the cost of this huge tank is about 66,000 dollars per each equivalent Okotoks' house), and the worse performance of using hot-water radiators instead of in-floor water as space heating system, regarding the poor yield obtained from flat solar collectors. The main parameters of this STES system can be calculated in order to compare against the Okotoks one, by taking its equivalent heating demand related to a single Okotoks' house (15,795 kWh/y). Hence, we can obtain: an overall cost of 128,000 dollars, STES water volume of 320 m^3, and solar collector area of 108 m^2. These poor numbers reflect the bad choice using a high-temperature heating system (hot water radiator instead of underfloor hot water) and shows the coupling effects between the three (solar, STES, and heating) systems involved.

The third project that we consider now as a reference point uses a small water tank for heating a single house. The Irish Galway project was initiated in 2006, [10]. It uses a 23 m^3 underground water very well insulated (wrapped by an EPS layer of 60 cm thickness) and six vacuum-tube collectors (2 m^2 solar area and costing €500 each one) for heating a single house (1,827 kWh/y) within a temperate climate (2,063 heating degree days). This project is important for us because it has demonstrated the economic feasibility of small solar+STES systems, which can reach reasonable investments (€ 28,344). In addition, from the detailed cost breakdown performed by Colclough and Griffiths [10], it is obtained a good starting point for developing now our economic analysis. For example, this project has shown that large fixed costs (€4,300) related to the many auxiliary systems (temperature sensors, valves, piping, controller, pumps, etc.) required, and the same fixed cost will be considered in our project.

Besides, the Galway's project provides some useful lessons:

1. The actual cost of the underground tank exceeds largely the sole cost of the stainless-steel tank (€ 5,350). The total cost of the water tank must include their insulation (€ 3,060), the soil excavation (€ 1,404), and other labors related to the underground sitting (the construction of a grave and another impervious layer) add € 7,800, increasing the total cost up to € 17,600.

2. Thermal stratification does not occur within this well-insulated tank, in which have been measured temperature differences down 2°C.

3. The falling prices of solar collectors and the relatively high cost of the solar installation (€900), has been recognized by Colclough as a reason for installing more collectors since the installation cost is almost a fixed cost. Following this concept, Colclough, Griffiths, and Smyth [11] have estimated by numerical calculation that the solar fraction of the heating demand could be increased by 50% by doubling the number of solar collectors, which implies a modest extra investment of €3,000 when it is compared against the overall cost.

Regarding the last point from Colclough, we can expect significant improvements by performing an economical optimization on the number of collectors. This analysis should be done by considering the performance of both, the solar system and the STES system. However, at present, there is not any modeling tool available for this purpose. Most of the works have performed thermal models of STES by using complex numerical codes, like TRNSYS or ANSYS [11–13]. However, regarding the high complexity of these tools, we have realized that these codes are not suitable for modeling altogether the solar and thermal behaviors and for taking all-in-hand its parameters, as it is provided in this work by developing an explicit numerical model. Otherwise, the TRNSYS and ANSYS codes are suitable for modeling systems having two main characteristics:

1. Fast-transient dynamic, in which a very-detailed time discretization is required, which can be solved by using a time step of about one minute.

2. Spatial gradients of temperature are relevant, which can be performed by using finite volume method.

The first characteristic is not actually relevant for modeling large-term (as seasonal) STES systems, in which the evolution of the tank temperature is very slow, according to the high ratio between energy stored and energy demanded every day. Therefore, in such kinds of systems is not necessary to consider time steps shorter than a day. The second characteristic is relevant for modeling huge underground STES systems, in which their large weight forbids us to insulate their bottom part as it occurs in the aforementioned Friedrichshafen's project. However, this is not the case with small tanks, as it is proposed here. Those heavy STES systems suffer noticeable heat losses, and high-gradient temperature profiles, in both, radial and axial directions. On the contrary, this behavior can be neglected within small well-insulated tanks, as the Galway project has demonstrated [10].

From these findings, we have developed a simple lumped-capacity thermal model for water tanks, which assumes that both (radial and axial) temperature profiles can be neglected and so, all the water can be considered as having the same (homogeneous) temperature. The axial profile can be minimized by putting the source heat exchange below the sink one (this is the opposite configuration usually used in huge tanks, which is created a stratified temperature profile in order to minimize the heat losses about the not-insulated bottom part of the tank), and so, causing a free-convection flow that counterbalances the stratification, as the Galway's project has conveniently used [11]. In addition for aboveground tanks, there is a uniform boundary condition (the outdoor temperature) that helps to create a homogeneous axial profile. So, the radial temperature profile could be neglected in small tanks; indeed, this effect not solely depends on the tank size. Regarding the very-well known thermal behavior related to the heat conduction within a body surrounded by a fluid convective cooling [14], the diffusion of heat along the radial axis is complemented by the convective heat losses at the outside surface of the tank: In "large" tanks the heat diffusion is relevant and the convective heat transfer can be neglected. Meanwhile, the opposite behavior occurs in "small" tanks; but, indeed, their relative importance (their quotient) is actually represented by the dimensionless Biot number:

$$Bi = h\, D/\lambda_w \tag{1}$$

where h is the convective coefficient of heat transfer (at the external surface of tank), λ_w is the thermal conductivity of water, and D is the tank diameter. In general, problems involving Biot <1 (in which the heat diffusion within the tank can be neglected) are simple, since they can be considered that the temperature field within the tank is homogeneous [14], and so, the single thermal resistance (and temperature variation) to be considered is the one related to the boundary convective layer. Let us note that for well-insulated aboveground tanks, the convective coefficient (h) does not involve solely the thermal resistance of the convective film layer; otherwise, it rather than represents the thermal resistance of the insulation layer (that is, the major thermal resistance involved here), defined by its thermal transmittance (U). The reader can check that for the largest tank considered here (D = 3 m, λ_w = 660 W/K.m, U = h = 0.1 W/m^{2}K), it is verified that Bi <1. Indeed, even observing some minor temperature difference, as the 2°C difference measured in the Galway's tank [10], it must be considered that the actual temperature of the tank's surface is always lower than the mean temperature of the tank, and so, this homogeneous model is conservative for estimating the heat losses. Besides, by placing the sink heat exchanger on the central axis, the heat is delivered to the house with a temperature higher than the average, and so, this model is again conservative.

2. Solar and thermal modeling

2.1 New system design

This conceptual design considers many vacuum-tube solar collectors for heating one water tank up to 120°C in order to provide space heating by water in-floor system. Regarding previous works (up to 85°C), this overheating can be achieved with a modest tank overpressure (2 bar) that can be easily withstand by commercial stainless steel tanks (designed with a relief valve at 3 bar), meanwhile, this tank doubles the useful heat capacity (from 120–33°C) of previous tanks (from 85–33°C). So, the water-glycol mixture is heated up to 125°C and the in-floor system is cooled up to 28°C in order to maximize the working range of temperature within the tank, by considering a 5°C temperature jump in both heat exchangers, similarly to the Galway's project. This 5°C difference is enough for using standard tubular-copper exchangers that provide the demanded ($\sim$10 kW) heat power while getting affordable costs [15].

On the other hand, our design intends to use a small tank having a storage capacity of between two to four weeks for the winter heating demand. A smaller tank has a lower cost and also, a smaller total area, which in turn implies lower heat losses and insulation cost. This small tank is designed to be heated only around one month previous to the winter demand in order to be ready for this exigent demand, but most part of the year this tank is actually not used, meanwhile the vacuum-tube solar collectors are used for heating the secondary demands. Let us note that, this kind of collector has a remarkable ability for collecting energy even during cloudy days. For instance, according to measured data of the vacuum-tube collector manufactured by Apricus, its yield during cloudy days is 25% of the yield obtained during clear days [16]. On the other hand, a flat collector would have a negligible yield during cloudy days, and even on sunshine days during cold winters.

2.2 Solar collectors modeling

The use of vacuum-tube collectors in order to maximize the solar yield during winter is a key within this design, instead of the flat collectors usually used in these tested projects. This point will be discussed now by considering the efficiency curve of commercial vacuum tubes and flat solar collectors (see **Figure 1**), which are provided by the European Solar Industry Federation [17]. The instantaneous efficiency (η) of any solar collector can be approximated by its optical efficiency (a_0) and their linear (a_1) and quadratic (a_2) heat-losses coefficients, as is described by Eq. (2). Here, T_m is the mean temperature of collector, which receives normal solar flux, I_n (W/m^2), and T_a is the ambient temperature [18].

$$\eta = a_0 – a_1(T_m – T_a)/I_n – a_2(T_m – T_a)^2/I_n \tag{2}$$

Let us note in Eq. (2) that both heat-losses terms are divided by the normal irradiation (I_n). Hence, regarding that flat collectors have higher heat-losses coefficients than vacuum-tube ones, this effect (penalizing flat collectors) is minimized in **Figure 1** by considering a very high (800 W/m^2) I_n value, for which both curves intersect at 70°C (by taking the gross area for the vacuum-tube collector, which is another subjective decision that clearly favors flatting collectors). However, this value does not represent by far an actual average condition. Although this flux could be observed as the total solar irradiation (I) on clear days, a flat collector would obtain

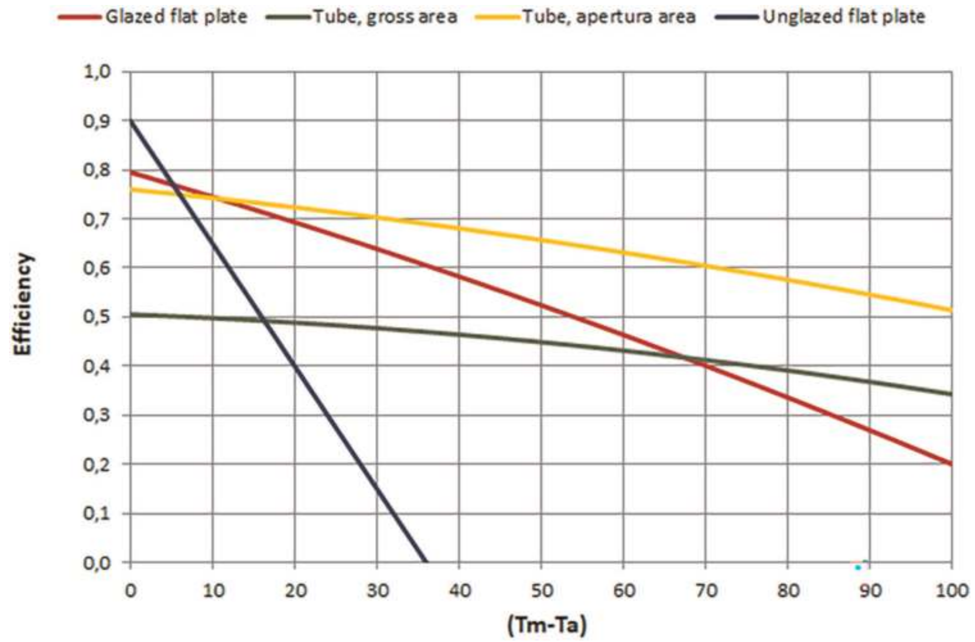

Figure 1.
Efficiency curve for different kinds of solar collectors.

this flux as its normal projection (I_n) only at noon (when its azimuthal angle is null) and twice along the year (when the elevation angle of the sun above the horizons matches normally the collector's tilt angle). Therefore, it is more accurate to consider both efficiency curves for lower I_n values. For instance, **Figure 2** are illustrated the efficiency curve for both collectors working on I_n = 400 W/m^2 and 200 W/m^2, for which are obtained intersecting points of 34°C and 17°C, respectively. These results show that, in these cases, the flat collector almost never gets higher efficiency than the vacuum-tube collector. In addition, for this last case (I_n = 200 W/m^2), the flat collector cannot get energy for temperature differences higher than 37°C, meanwhile, the vacuum-tube collector still gets a remarkable 36% efficiency in this case.

Let us remark that these low values of solar normal flux do not represent necessarily a cloudy-day condition. For example, let us consider now a fully sunny winter day (I = 800 W/m^2) in the Friedrichshafen project (having 38°-inclined collectors) at 4 pm, that is, when the elevation angle of the sun over the horizon is 2° and thus, the zenithal-angle of the sun with the collector's normal is 50°. For this condition, the sun rays present an azimuthal angle of 60° onto a south-oriented flat collector. So, the product of their cosines (cos60° x cos50° = 0.32) leads to getting a normal irradiation flux over the flat collector I_n = 257 W/m^2, for which the maximum temperature difference, this flat collector could reach is 47°C. Therefore, it can be inferred that this flat collector always would obtain negligible winter yields working with 55°C hot-water radiators, as was observed in the Friedrichshafen's project. Otherwise, in this case, the vacuum-tube collector gets 34% efficiency, which is calculated by taking I_n = 514 W/m^2, regarding that for this case, the azimuthal projection (cos60°) must not be considered, due to this cylindrical geometry. This comparison can be extended, for example, to a fully sunny summer day at 4 pm when the elevation angle of the sun is 17° and then, the azimuthal angle over collectors is 35°, leading to I_n = 327 W/m^2 for the flat collector and I_n = 654 W/m^2 for the vacuum-tube collector.

Therefore, following the previous discussion, we can conclude that **Figure 2** induces us to make a huge mistake that is to compare both collectors as working on the same I_n value. Another way of saying this is that the crossing-point of both curves cannot be used at all as a criterion for comparing the performance of flat and

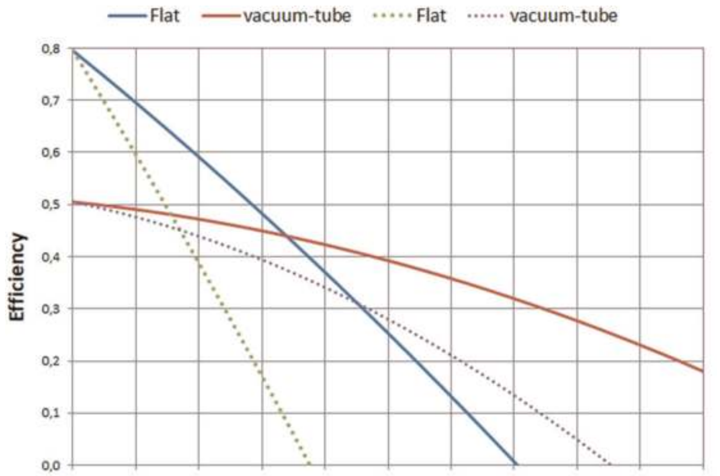

Figure 2.
Efficiency of flat and vacuum-tube collectors (I_n = *400 and 200 W/m*^{2}*).*

vacuum-tube collectors. Let us note that a flat collector receives a variable azimuthally-projected solar area along the day, meanwhile, a cylindrical collector always offers the same azimuthally-projected solar area. Although a full discussion of this issue depends on many factors, such as the day of the year and the latitude of the location, etc., maybe we could consider now a useful analogy. Regarding the total solar energy received along the day (G, kWh/m^2), the flat collector can be represented by a fixed PV panel, and meanwhile, the vacuum-tube collector could be represented by another PV panel mounted onto a one-axis solar-tracking system. Hence, we can compare the yield of both collectors by using the well-known result that the one-axis tracking PV panel produces about 30% more energy than the first fixed PV panel [19]. Therefore, and taking into account that our solar model calculates the G received for tube collectors and not for flat collectors (see the solar_trajectory.xls file in [20]). It will be conservatively estimated the G values received by flat collectors by reducing 25% the G values calculated for cylindrical collectors. And now, let me be completely clear about this point. In my opinion, it is completely unforgettable that most solar researchers have traditionally neglected this mismatch behavior between flat and vacuum-tube collectors; I guess that this is due to some aversion against vacuum-tube solar collectors, which mostly are manufactured in China. However, and in order to be fair for both kinds of collectors, I have to note also that vacuum-tube solar collectors have a major drawback, regarding their concerns about overheating, which potentially can be very dangerous (especially considering heat-pipe collectors with an integrated water tank above vacuum tubes), but, precisely this kind of solution as is studied here (by using large water tank and controlling system) should be the “silver bullet” for this weakness. In my opinion, from the selection of flat solar collectors within most projects performed up today, we can realize that this aversion exists. As we will discuss here, the huge costs reached for all projects performed up today (by using a huge STES system) are related to this choice, and this is the major cause of the failure of this technology. A failure that may cannot be overpass in the future, since nowadays is been coming to another solar technology with a better perspective for solving the heating household demand. This novel technology is the air/water heat pump (having efficiencies around 400%) that can be linked with photovoltaic panels in order to get a sustainable solution, as well as the proposed (solar + STES) technology, does.

2.3 Thermal model of STES

The STES system is modeled on these useful assumptions for simplifying:

1. The condition of temperature surrounding aboveground tanks is modeled by using the monthly averages of outdoor ambient temperature. This assumption is reasonable by considering that the tank temperature varies slowly, and so, any fast variation on the ambient temperature is counterbalanced and can be neglected in order to calculate the monthly heat losses of the tank.

2. The fully time-related terms involved in the STES energy balance (that is, thermal powers and temperatures) are considered by means of their monthly averages. This is a reasonable assumption that the heat transfer mechanisms (conduction and convection heat losses) involved are described by linear equations and so, they both are proportional to the difference of temperatures. Therefore, any fast fluctuations are counterbalanced when this term is integrated along one month. However, let us point out that by considering a numerical

scheme based on monthly time steps, it will be introduced several numerical errors, and for this reason, after performing this model, another model will be performed by using daily time steps in order to verify the accuracy of the results obtained with the previous monthly model.

3. The field of temperatures within the water tank can be considered homogeneous, T. This assumption is reasonable according to its low Biot number, as it was previously discussed.

Working on the previous three hypotheses, the time evolution of the tank temperature can be calculated by means of the thermal model based on lumped capacities [14]. Taking this model and by considering now the energy equation, the rate of internal energy can be calculated by counterbalancing the solar power (Q_{solar}) gained with both extracting powers, the heat losses to the surrounding ambient (Q_{amb}) and the power delivered to the household in-floor heating system (Q_{heat}):

$$M\,c(dT\,(t)/dt) = Q_{solar}(t) – Q_{amb}(t) – Q_{heat}(t) \tag{3}$$

In this equation, the water mass and its heat capacity are noted by M and c, respectively. Thus, the annual evolution of the STES temperature can be described by using their monthly averages going through a twelve-equation system, as:

$$M\,c\,(dT_1/dt) \sim= M\,c\,\left(T_2{}^1 - T_1{}^0\right)/\Delta t = Q_{solar}{}^1 – Q_{amb}{}^1 – Q_{heat}{}^1 \tag{4}$$

$$M\,c\,(dT_2/dt) \sim= M\,c\,\left(T_3{}^1 - T_2{}^1\right)/\Delta t = Q_{solar}{}^2 – Q_{amb}{}^2 – Q_{heat}{}^2 \tag{5}$$

$$M\,c\,(dT_{12}/dt) \sim= M\,c\,\left(T_1{}^1 - T_{12}{}^1\right)/\Delta t = Q_{solar}{}^{12} – Q_{amb}{}^{12} – Q_{heat}{}^{12} \tag{6}$$

In this system is approximated every *n-teenth* (n = 1,2 … 12) temperature rate (dT_n/dt) by its difference quotient along its monthly time step, $(T_{n+1} - T_n)/\Delta t$, and so, we can transform the original system of differential equations in another (simpler) system based on algebraic equations. The supra-index in powers and the sub-index in temperatures denote the ordinal monthly number, and the supra-index in temperatures denotes the number of the numerical iteration performed for obtaining an accurate solution. This system describes an explicit numerical scheme that can be solved by performing an iterative procedure. Thus, starting with a seed value for the first month ($T_1{}^1$), the first value of every month can be cleared going through (Eqs. (4)–(6)). Here, the last Eq. (6) gives us the new value for the first month ($T_1{}^2$), from which this iterative procedure starts again, and continues until the whole system converges to the stationary periodical solution, which describes the temperature evolution of the tank. This numerical code was performed on a spreadsheet (see Complementary Material, in [20]) and from our results, we have observed that usually, only little iterations are needed. This behavior is expected, according to the physical characteristic of this system, which is an energy dissipater. So, we have chosen a spreadsheet instead of any procedural language for developing our numerical tool, considering its advantage of providing explicit all-in-hand modeling.

We have to calculate now the three power terms, Q_{solar}, Q_{amb}, and Q_{heat}, in order to solve the previous algebraic system (Eqs. (4)–(6)). The first term (solar power) depends on the solar resource and the efficiency of solar collectors. For N collectors having collecting area A_c and instantaneous efficiency $\eta(t)$, the instantaneous solar power collected from a normal solar flux $I_n(t)$ is given by:

$$Q_{solar}\ (t) = N\ A_c\ \eta(t)\ I_n(t) \tag{7}$$

Actually, we are only interested in obtaining the monthly averages of the collected solar energy, ${E_{solar}}^n$. So, the monthly balances of powers (Eqs. (4)–(6)) will be substituted by the monthly balances of energy. However, it is cumbersome to integrate Eqs. (7), due to the high variability of the solar resource. On the other hand, the single solar data worldwide available are the monthly averages of the daily solar energy on ground level (G^n). Thus, this lack is now solved by introducing monthly average factors (α^n x G^n), which take into account the relation between both monthly solar irradiations, the received on ground level and the received on the collector when it is elevated a given tilt angle (φ). By using these factors, the monthly average of the collected energy can be calculated by:

$${E_{solar}}^n = N\ A_c\ \eta^n\ \alpha^n\ G^n \tag{8}$$

In this equation, we have been introduced the monthly averages of the collector's efficiency, η^n, which (from Eq. (2)) can be calculated by substituting the actual collector mean temperature (T_m) at the *n-teenth* month by the tank temperature calculated at the previous month, $T_{n\text{-}1}$:

$$\eta^n = a_0 – a_1(T_{n-1} – T_a)/I_n – a_2(T_{n-1} – T_a)^2/I_n \tag{9}$$

Here, let us note that the mean collector's temperature is around 5°C, higher than tank temperature by taking into account the temperature jump in the heat exchange. However, also the ambient temperature could be considered around 5°C above its daily average, according to the fact that the collector gets its highest efficiency mostly around noon, and so, these opposite effects are canceled.

The α^nxG^n factors introduced in Eq. (8) must be calculated according to the latitude of the location, the day of the year and the collector's shape (cylindrical or flat), and they can be calculated from many solar codes available in the literature. Here is provided with a code programmed for cylindrical collectors (see in solar_trajectory_Bariloche.xls [20]), based on the well-known equations that describe the apparent trajectory of the sun [1, 21]. By using this code, the procedure from which the calculation of the α^nxG^n factors can be described by four steps:

1. To calculate the sun trajectory and its normal collector's area along the day for every month. This step is performed by setting the input data (cells B4-B7) by considering the mean day of every month (for example, d = 15 for January, etc.). Thus, cells A14: F255 are obtained the intended results.

2. To calculate for every month the daily solar energy received on the ground (G) for a given (constant) direct solar irradiation, I. This calculation is performed by setting to zero the collector's tilt angle (cell B6) and so, the calculated G value is obtained in cell B10.

3. By using this I-G calculation and the known values of G^n, now we can calculate (by iterating) the monthly values of I, that is, the equivalent direct solar irradiation that provides the same energy on the ground. Of course, this is a simplified model that does not consider the diffuse solar irradiation (that is an

isotropic term), but, for the goal looking for here (to get the monthly averages of collector's production), this is a reasonable approximation.

4. Then, by using these monthly *I* values it is calculated the solar irradiation that would receive a cylindrical collector ($\alpha^n x G^n$) mounted with a given tilt angle.

Although at a first glance this procedure could be cumbersome, it is a well-known methodology; there are many similar software applications for calculating the solar irradiance over a collector as a function of its tilt angle. For example, the reader can study the simulating tool developed by NASA [22] for studying the *G* value for different tilt angles in any worldwide location. This issue has also been studied in the literature. Duffie and Beckman [23] have suggested tilt angles equal to the latitude for maximizing the annual yield. Tang and Wu [24] and Handoyo, Ichsania, and Prabowo [25] have recently proposed another criterion.

The energy losses by the tank (to the ambient for aboveground tanks, or to ground for underground ones) along the *n-teenth* month, ${E_{amb}}^n$, is calculated in Eq. (10) by integrating the Q_{amb} power term during its time step (Δt_n), and by considering the tank temperature of the previous month, T_{n-1}. In Eq. (10), λ and *s* are, respectively, the thermal conductivity and thickness of the insulation material, and *A* is the overall external area of the tank.

$$E_{amb}{}^n = (\lambda/s)A\left(T^{n-1} – T_a{}^n\right)\Delta t^n \tag{10}$$

Remembering that the monthly averages of energy consumed by the space heat system (E_{heat}) and the monthly mean ambient temperatures are given by **Table 1**, now all terms of Eqs. (4)–(6) can be explicated. So, these equations can be solved by the iterative procedure described before, by:

$$M\,c\left(T_2{}^1 - T_1{}^0\right) = E_{solar}{}^1 – E_{amb}{}^1 – E_{heat}{}^1 \tag{11}$$

$$M\,c\left(T_3{}^1 - T_2{}^1\right) = E_{solar}{}^2 – E_{amb}{}^2 – E_{heat}{}^2 \tag{12}$$

$$M\,c\left(T_1{}^1 - T_{12}{}^1\right) = E_{solar}{}^{12} – E_{amb}{}^{12} – E_{heat}{}^{12} \tag{13}$$

Let us discuss now the accuracy of this numerical methodology. There are two numerical approximations introduced by this explicit one-step scheme, related to the using of the temperature at the previous month (T_{n-1}), instead of using (T_n) for calculating the heat losses to the ambient (Eq. (10)) and the collector's efficiency (Eq. (9)). These two approximations together with the monthly approximation of the temperature rate (dT/dt), can be improved by reducing the time step, which is similar to any other numerical solver. This way, for all cases studied here, is provided three numerical codes (see *Complementary Material* in our Mendeley Dataset, [20]. The first code (namely 12 months) is based on a monthly time step (Eqs. (11)–(13)). The second code (namely 365 days) follows the same physical approximations that the previous one, but based on a daily time step and so, it gives us a more accurate solution. As it will be discussed in the next section, the major improvement achieved is related to the calculation of efficiency (Eq. (9)), which on the monthly modeling has tended to underestimate the efficiency during the winter months, which in turn penalizes the system's performance. In addition, there is a fourth approximation "hidden" in our numerical modeling, which is related to the calculation of the α_{n} factors. This approximation is programmed on both previous codes by using the same monthly values calculated, as

	Monthly heating demand		Ambient mean temperature
	%	kWh	(°C)
January	28.6	4,521	−12
February	11.9	1,884	−8
March	3.4	533	−2
April	0.9	148	5
May	1.8	281	10
June	—	0	13
July	—	0	17
August	—	0	18
September	—	0	12
October	—	0	5
November	16.3	2,569	3
December	37.1	5,855	−9
Annual	100%	15,795	4.5

Table 1.
Monthly fractions of heating demand and ambient mean temperatures for Okotoks.

was previously described by using our solar (solar_trajectory) code [20]. This code calculates the α_n factors going through the daily sun apparent trajectory by using a time step of 0.1 hours. Therefore, here is also provided with a third code (namely full365) that includes a daily calculation of these α_n factors. These calculations can be performed day by day going through a very time-consuming task, by using our solar code (solar_trajectory). Fortunately for the reader, this procedure has been already programmed by using a Visual Basic subroutine that is provided too (clicking the right button of your mouse over the name of the sheet and then, selecting the option 'view code'). Here, is also provided with a second sheet (namely 0.01 h) that includes a more accurate (taking 0.01 h time step) calculation for solar_trajectory.xls, in order to minimize the error of this procedure too. Hence, now the accuracy of our first monthly model (12 months) can be estimated by comparing its performance against this most refined daily model (full365) developed. According to the observation that this last model provides always solutions with very small variations of the main variable (that is, the tank temperature varies down 0.3°C in every daily step), the numerical error of this model can be estimated as negligible and thus, the total error of our first monthly model can be estimated by comparing against this last code; this way, we have observed always solutions within the +/− 10% bandwidth error.

3. Results

3.1 Results for our previous design

Let us summarize now the major results obtained by using our previous design, which is based on the present design developed here. So, that design is similar to the present design, but has some minor differences:

1. The water tank is heated up to 85°C (instead of 120°C);

2. The system is designed to only satisfy the space heating demand (instead of including other demands);

3. It is not used standard heaters as a backup system.

This design was performed in our previous work [1]. Summarizing, the analysis performed had found several different behaviors:

a. For small tanks, the system performance is better as much as the tank size is increased. This expected behavior has led to traditional projects using very large STES systems.

b. For tanks larger than a certain size, the opposite behavior is found, that is, the system performance is worse as much as the tank size is increased. In this case, was observed that the drawback of larger heat losses (due to the larger tank area) counterbalance the positive effect of having a larger heat storage capacity.

c. For small tanks, it is mandatory to maximize the collector yield during winter, and so, very high collector's tilt angles must be used, like 78°. It also was observed that this high tilt could be obtained by mixing some collectors on a more common tilt angle (like 45°), and others put onto vertical walls (90°).

d. Otherwise, for large tanks (that works properly as a seasonal storage system) is not mandatory to use high tilt angles, and lower angles (usually used for maximizing the annual yield, like 45°) can be used.

e. The results obtained for vacuum-tube solar collectors are noticeable better than for flat ones. Flat collectors get poor average efficiencies and are almost null during winter. Meanwhile, vacuum-tube collectors can obtain some interesting yield during winter, even on cloudy days.

f. These thermal performances are related to their economic performances. It is possible to fulfill the heating demand by using a small (72 m^3) aboveground water tank with 18 vacuum-tube collectors (solar area 37 m^2), costing about 30,500 euros. On the other hand, for flat solar collectors it is required to install a larger tank (170 m^3) and 23 flat collectors (solar area 48 m^2), and so, the overall cost increases to 45,400 euros if an aboveground tank is installed. However, maybe this large tank causes an undesirable visual impact and would be preferred an underground siting, in which case the overall cost increases to 112,500 euros.

The calculation of any solution implies choosing a tank size (M) and calculating the minimal number of solar collectors (N) needed in order to satisfy the space heating demand, that is, that the water temperature of the tank works always within the usable range (33–85°C) in order to provide the space heating demand. However, in this procedure, we must keep in mind that the dynamical model considers only average parameters (temperatures, etc.). So, during very cold days and especially when very small tanks are chosen, this calculation could not be conservative, since the thermal storage capacity of the water tank could not be enough for overpassing such an event. Therefore, let us study now the behavior of the STES system during the worst weather event (having several fully cloudy days) that we will define as a ten-day cloudy-weather event. This event is calculated in our model by means of not considering the average monthly solar irradiance, and instead considering the collector's yield obtained during cloudy days. So, we are calculating the (higher) number of collectors needed for solving this extreme condition. These N numbers are illustrated in **Table 2** (in brackets) for φ = 78°, together with the usual average solution. Here is observed that this very cold winter leads to very poor performances for small tanks, which must be supported by using much more collectors. Otherwise, large tanks can easily manage this scenario; for example, case **A** (M = 170 m^3) provides enough storage for one month, and so, the number of collectors are the same in both (average and worst) cases.

Table 3 summarizes the breakdown of cost (for the case φ = 78° and ten-day storage capacity) for the previous cases studied in our previous work [20]. It is interesting to note that the larger tank (case **A**) obtains a total cost slightly higher than the other ones, but it provides the largest storing capacity (one month) that can fully provide the heating demand. However, in this case, it should also be evaluated the visual impact of placing this large aboveground tank close to the house. So, let us study now another option for providing this large storage capacity, which is performed by using the next smaller tank (case **B**) with eighteen solar collectors, so getting a total cost of €32,200.

Table 4 repeats the previous analysis by using flat solar collectors (STES_Okotoks-Flat collectors, in [20]) having each one the same solar area (2.088 m^2) as the previous vacuum-tube collectors, but, of course, they both have different efficiency curves,

M (m^3)	*N 78°(#)*	$\eta_{collector}$ (78°)	*N 45°(#)*
1,360	8(8)	69%	8
170-**A**	8(8)	63%	9
72-**B**	16(18)	59%	19
21-**C**	27(34)	58%	33
4,6-**D**	30(76)	57%	36

Table 2.
(N, M) solutions for vacuum-tube collectors.

	A	B	C	D
Collectors	€4,800	€10,800	€20,400	€45,600
Tank	€20,031	€11,362	€5,038	€1,849
EPS insulation	€6,290	€3,515	€1,554	€555
Siting preparation	€68,000	€28,800	€8,400	€1,840
Fixed costs	€4,344	€4,344	€4,344	€4,344
Total (underground)	**€103,500**	**€58,800**	**€39,700**	**€54,200**
Total (aboveground)	**€36,400**	**€30,500**	**€31,600**	**€52,400**

Table 3.
Breakdown of costs for different solutions (φ = 78°).

M (m^3)	*N 78°* (#)	$\eta_{collector}$ (78°)	*N 45°*(#)
1,360	13(13)	54%	14
573	12(12)	48%	12
170-**A**	23(23)	28%	28(28)
72-**B**	51(76)	23%	61(90)
21-**C**	62(211)	22%	76(239)
4,6-**D**	62(∝)	22%	75(∝)

Table 4.
(M, N) solutions for flat collectors (tilt angles 78° or 45°).

according to **Figure 1**. The performance of these flat collectors has been simulated (following our previous discussion) by reducing 25% the solar factors α^nxG^n previously calculated for vacuum-tube collectors. Similarly, the I_n fluxes previously calculated are now 25% reduced and then used in the efficiency equation (Eq. (9)).

Now, by comparing **Tables 2** and **4**, we can observe that flat collectors always get lower efficiencies than vacuum-tubes ones and that their efficiency decreases strongly as much as the tank size is reduced, and so, their working temperature is increased. Another difference regarding vacuum-tube collectors is that flat collectors achieve negligible efficiencies during winter and so, their performance is highly penalized when small tanks are used. Otherwise, it is interesting to note that their performances are very reasonable by using large tanks, in which they can take advantage of their higher efficiencies during summer (**Table 4**).

In order to estimate the total cost of these alternative designs for Okotoks, it will be assumed that the unitary cost of flat collectors is equal to previous vacuum-tube ones, regarding that there is a wide range of commercial models for both kinds of collectors and so, different cost choices. **Table 5** shows the total investments for the previously studied cases. Here is can be observed a different behavior regarding the previous systems with vacuum-tube collectors, since now the best choice is always obtained with the largest tank (case **A**). In addition, this large tank can support the collectors installed on different tilt angles.

It is interesting to compare this case (solar area 37 m^2) with the Okotoks' project that uses a similar collector's area (44 m^2 per house). This 170 m^3 tank gets an average efficiency of 82%, which is higher than the Okotoks STES efficiency (60%), due to their lower size and higher thermal insulation (the Okotoks reservoir uses 583 m^3 of rocky underground per house). The comparison with the Friedrichshafen's project is also interesting since both use water tanks as STES system. Here is observed that the German project uses a larger tank (320 m^3) with low efficiency (60%) and a higher

Tank siting -tilt angle	A	B	C
Underground-78°	€112,500	€93,600	€146,000
Aboveground-78°	€45,400	€65,400	€137,800
Underground-45°	€116,400	€102,600	€163,000
Aboveground-45°	€48,400	€73,800	€154,600

Table 5.
Total costs for flat collectors.

solar area (108 m^2) too, leading to a noticeable higher overall cost (128,000 U$) per equivalent Okotoks' house.

Finally, **Table 5** is presented the total cost of these cases for underground tanks, calculated from the Galway's underground tank (€17,600). Here we can observe that an underground tank always leads to a remarkable higher cost than the aboveground option. Hence, since a small tank can be conveniently be insulated, we will prefer aboveground tanks. Moreover, as we will discuss in the next section, this aboveground could be installed within the greenhouse near the house, and this way, its heat losses can be useful for warming the greenhouse.

3.2 Results for the new design

The new design takes advantage of four main concepts:

1. The utilization of other secondary demands of heat throughout the whole year in order to fully exploit the collector yield. Regarding that space heating demand is very concentrated during four months in cold locations as Okotoks (from November to February, 94%), it was observed in the previous study [1] that the small tank cannot store the solar production along the year, and so it must be avoided during seven months (being needed just one month for heating the tank in advance to cold season). Hence, here is exploited this surplus of heat to fulfill other demands, like warming a greenhouse (during spring and autumn) and swimming pool (during summer).

2. Here is allowed to help the solar production during winter (the most exigent demand) by using small standard electric heaters (consuming total energy down 10% of annual solar production). This backup system helps us to downsize the STES (the main cost), as we shall see in this section. This choice is a smart economical optimization since these electric heaters only must work during the extremely cheap (about 0.1 euros per kWh) valley tariff.

3. The capability of a commercial stainless steel water tank for withstands slight overpressures (up to 3 bars). Hence, in this design is overheated the water tank up to 120°C (2 bars) and this way, the usable heat (from 120–33°C) is doubled regarding previous design.

4. The low cost of these tanks that are massively manufactured for daily-storage solar & heat pump applications (space heating and sanitary hot water). These tanks are available up to 5,000 liters costing about 3,000 euros, and including high-quality thermal insulation, internal double heat exchanger, and thermostat and standard electric heater. So, we can build the whole STES system (by adding a water pump and controlling unit, adding 2,000 dollars) easily by installing one or more tanks.

This novel design was developed on new software [26] that is similar to our previous dataset but includes the calculation of the secondary demand and other minor changes. The managing strategy followed here combines different objectives along the year:

1. It maximizes the secondary production from spring to autumn, by setting the tank temperature at 30°C during this warm period. So, the secondary demand is

calculated every day as the one required in order to get an equilibrium balance of energy (that is, the fully heat production from solar collectors is used as secondary demand). This low temperature (30°C) was set according to fulfill the main secondary demands considered (warming a greenhouse and swimming pool). Actually, this 30°C level is not enough for providing sanitary hot water demand (another secondary demand considered), but this last demand (calculated as 200 liters of 40°C-heated water, or 9.3 kWh per day) is almost neglected (about 1%) compared to the total secondary demand produced every day. So, the production of sanitary hot water would not change the energetic balance calculated here; maybe it implies some minor complexity (another 200 liters tank heated up to 45°C every day by solar collectors) that will not be considered here.

2. The water tank is heated up to 120°C before the peak winter demand starts (during December); it is observed that a month is enough for this purpose. Therefore during November the tank is heated by solar collectors meanwhile the space heating and sanitary hot water demands are fulfilled, and all the other secondary demands are avoided.

3. The water tank is continuously cooled during December since the demand is higher than the solar yield, but the backup electric heaters are used in order to keep the minimum usable level (33°C) on the last day of December.

4. The tank temperature is increased along January without using the backup system since the primary demand (avoiding other secondary demands) is lower than the solar yield. This way, it is observed that the tank is heated at about 70°C on the last day of January.

5. During February and March, it is considered that the "danger" condition has been overpassed (there is still some heating demand, but it is remarkable lower than the previous one). So, our strategy for this period consists in setting the water tank to 45°C, in order to provide some margin for any "bad weather event" that might occur. Therefore, the system could provide another secondary demand (to warm the greenhouse), starting with a "heat punch" that is calculated in order to get the 45°C desired level.

6. From April to October (the warm season), the tank is set to 30°C (starting again with a "heat punch"), and all solar production is available for other secondary demands.

Following this managing strategy, **Table 6** shows the results obtained by a sensitivity analysis on the number of collectors (N) for 10 m^3 water tanks (that could be built by using two 5,000 liters commercial tanks). All cthese cases are described in our Dataset [26], cases #1 to #5. In all these cases is calculated the annual heat production from solar collectors, E_{solar}, and the annual heat production from electric heaters, E_{elec} (it absolute value and percentage of E_{solar}), and it is also noted the continuous electric power, P_{elec}, that would be required during the valley tariff (8 hours per day), and the number of months of the year that the system could provide these secondary demand (warming a greenhouse or swimming pool). Let us note here that the total fixed demand to fulfill (space heating, 15,795 kWh/y and SHWD, 3,407 kWh/y, totalizing

N (#)	E_{solar} (kWh)	E_{elec} (kWh)	E_{elec} (%)	P_{elec} (kW)	Months 2nd heat
10	53,760	6,424	11.9	15	8.0
15	74,259	3,664	4,9	11	8.6
20	94,363	1,852	2.0	7	9.0
25	117,243	768	0.7	3	10.6
30	139,889	99	0.1	0.4	11.0

Table 6.
Sensitive analysis for number of collectors, N, *and backup heaters* (M = $10\ m^3$@120°C).

19,202 kWh/y) is several (among 3 and 7) times smaller than the total energy produced by including these secondary demands too. In all these cases, the thermal efficiency of the STES system is very high (around 95%), as much as the average collector efficiencies (around 67%). Although the tank must be overheated during winter, and in this condition, the collector efficiencies are down to 40%, these annual efficiencies are high because most parts of year the collectors (and tank) work on low temperatures.

The sensitive analysis performed in **Table 6** is now related to cost analysis (**Table 7**), by considering each 5,000 liters tank (€4,000), the auxiliary systems (controlling system and pump, €2,000), and each 20-tubes (2.088 m^2 solar area) collector (€500, similar to our previous work). The cost of electricity is always considered as 0.1 €/kWh, according to the valley tariff, for the backup system and for calculating the annual saving obtained compared to standard system (fully providing heating by electrical heaters).

Table 7 shows that higher the number of collectors is lower the payback period is, although with slight differences (10%) above twenty collectors. So, the optimal solution could be 20 to 30 collectors, according to the investment desirable and the secondary heating demands that actually are required. This last point is remarkable; the previous analysis is based on considering that the fully solar production is utilized, otherwise, the cost optimization would noticeably change. For example, let us consider now the opposite behavior, that is, without others' secondary demands (except SHWD). In this condition, the total heating demand is 19,202 kWh/y and so, the maximum annual saving achievable is €1,920 (minus the backup consumption). So, by calculating again the payback period for this condition (the last column in **Table 7**), are obtained values from 11.3 to 13.1 years, being the optimal around 15 collectors. Hence, we can conclude that an optimal point for every condition is around 20 collectors.

N (#)	Total cost (€)	Backup (€/y)	Saving (€/y)	Payb. (years)	Payb.* (years)
10	15,000	642	4,700	3.2	11.7
15	17,500	366	7,100	2.5	11.3
20	20,000	185	9,300	2.2	11.5
25	22,500	77	11,600	1.9	12.2
30	25,000	10	14,000	1.8	13.1

** represents the payback period without secondary demands*

Table 7.
*Cost analysis for previous (**Table 6**) cases.*

M (m^3)	η_{tank} (%)	E_{solar} (kWh)	E_{elec} (kWh)	E_{elec} (%)	P_{elec} (kW)
10	95	94,363	1,852	2.0	7
50	89	94,704	744	0.8	3
100	82	91,354	0	0	0
100*	71	78,721	0	0	0

** represents the payback period without secondary demands*

Table 8.
Sensitive analysis for tank size (N = 20).

Let us study now the sensitivity analysis about tank size, M. It is possible that a larger tank could obtain a better performance since the backup system would be less required. This is true, but it must be counterbalanced with higher heat losses (due to the larger tank area), and higher costs as well. **Table 8** shows this effect (for $N = 20$) by considering $M = 10$, 50 and 100 m^3. This last case is repeated (*) for considering a slightly different strategy; in this, the large storage capability is exploited for collecting energy during the summer (this tank can store about 42 days of winter heating demand), what could be useful is the dweller does not have a swimming pool, in order to use this stored energy during the spring and autumn seasons. This way, the usable season for the greenhouse could be started before (January) and ended after (October) that is, extending it two months. **Table 8** shows that a larger tank suffers larger heat losses that overpass the benefits of having a larger storage capacity (that is, the overall energy production achieved in this way is lower). Besides, the total cost related to a larger tank is increased noticeably, being €52,000 and €92,000 for M = 50 and 100 m^3, respectively.

Finally, all the previous analyses show that the solar, thermal and economical behaviors are strongly linked. Hence, simple explicit modeling as it is performed here has been demonstrated to be useful for optimizing altogether the system parameters.

4. Conclusions

In this work was studied the performance of solar + STES systems based on many vacuum-tube solar collectors and a small well-insulated aboveground water tank, which is used to provide all the heat demands related to a single-family house in cold climates. This approach is innovative in many manners. These kinds of systems have been traditionally designed to fulfill the space heating demand of many houses together in cold climates that are concentrated during winter, but in this case, it is also designed to satisfy other secondary demands of dwellers along the year, like sanitary hot water, and to warm a greenhouse (from spring to autumn) and a swimming pool (during summer). Besides, the traditional approach followed in most projects has used many flat solar collectors with a huge STES that provides seasonal storage. On the contrary, here is proposed to use many vacuum-tube collectors and a short-term STES, which provides a solution with noticeably lower costs.

This work has discussed the radical differences between both designs from a designer point of view, that is, to perform “inverse engineering” (from results to design), in order to understand the motivations behind each design. It has shown that there are many hidden concepts supporting the traditional design. So, the choice of a huge STES seems to be motivated by the expectative about reaching lower costs and heat losses, due to scaling up the reservoir size. As it was discussed here, none of both issues has been actually achieved in present large projects. Firstly, it is true that the volume/area ratio can be reduced by enlarging the tank size, which could lead to getting lower heat losses and costs as well. However, this effect is actually overcome by higher heat losses caused by the fact that is not possible to put thermal insulation under a huge and overweight tank. For example, the Friedrichshafen's project uses a 12 m-height underground tank (walls built by 30 cm-thickness reinforced concrete and a stainless steel 2 mm liner) in which there is no insulation on its bottom third part, and it achieves overall heat loses about 40%, similarly to the Okotoks' project on its huge heat reservoir built by deeply drilling the rocky ground. Secondly, the cost of building a huge (12.000m^3) tank as the Friedrichshafen's project uses, is noticeably increased by the requirements of mounting it within an underground site, since such as huge tank would cause a high visual impact if it is mounted aboveground. Furthermore, we have already discussed in the previous work that the ultimate motivation behind the use of a huge heat reservoir is to support the utilization of flat solar collectors. This kind of collector cannot give yield during winter (when the space heating demands occur) in cold climates; so, this choice obeys us to consider a seasonal STES, in which the flat collectors accumulate heat during summer.

On the other hand, the novel design proposed here uses many vacuum-tube collectors, which can obtain a remarkable yield during winter. This way, this solar system can be supported by a short-term (providing down one month of the heating demand) STES system, which in turn reduces noticeably the overall cost. This way, this short-term STES can be performed by using an aboveground stainless steel water tank, which can be easily wrapped with thermal insulation in order to achieve overall heat losses of about 5%, and achieving overall cost remarkable lowers that the traditional design.

According to the performance of both designs, the traditional design and novel one proposed here, we can point out that the preference for flat collectors is the primary cause behind the unaffordable costs achieved by all projects developed up today. We guess that this issue has been overlooked in previous analyzes, but we want to be clear about this. There are many customers reluctant to put vacuum-tube solar collectors in their homes. This is true especially in Europe, where is forbidden to install collectors that waste water from the distribution grid. This situation can occur (mostly in summer vacancies, that is, without hot-water consumption) for vacuum-tube collectors. In this case, these collectors can suffer a dangerous overheating solved by discharging steam to the ambient. This solution could be acceptable for use as a second (security) system, but this is completely unacceptable for using periodically (that is, working actually as a controlling system). For example, in the event that it happened that this pressure-relief valve gets stuck and the overpressure cannot be released, the water tank could suffer a catastrophic rupture, which nobody wants to occur in his home. Perhaps, this weakness of the design of vacuum-tube collectors is actually the major limitation for their massive application. It is funny, but this overheating is cause for their successful improvement in getting lower heat losses (achieved by using better sensitivity coatings with lower infrared emissivity), as was shown in a recent work. In this work is discussed how this drawback could be solved by just making a step back in the development of better sensitive coatings [18]. This solution is affordable and can be easily applied by manufacturers, instead of the complex and expensive solutions that are currently under development, which propose smart selective coating with temperature-controlled solar light transmittance [27, 28]. Moreover, in this work, Juanicó also proposes to enlarge the number of vacuum tubes and the size of the water tank of the average collector (about 40 tubes and 500 liters water, instead of the average 20-tubes 200-liters collector) in order to noticeably enhance the capability of the solar collector for providing the hot water demand during several cloudy winter days, as well as this design noticeably reduces the risk of overheating. This new design of collector intends to overcome the present limitation of solar collectors that, at the present, satisfy only partially the average dweller demand.

According to this last design, we can realize now that the small (solar + STES) system proposed here follows this concept. A relatively large tank size (10 m^3) can be enough large to overcome concerns about overheating during vacancies. Moreover, the thermal–hydraulic configuration used here (in which the heat produced by solar collectors is transferred to the tank only when the controlling system does that) forbids the risks of overheating at the tank. Besides, the high-temperature (up to 120° C@2 bar) heat reservoir proposed here helps to overcome this concern, because the thermal efficiency of commercial vacuum-tube collectors decreases noticeably working at this temperature. These features altogether should convince us to use vacuum-tube collectors as a feasible and safe option.

This work has studied the advantage of using a STES that can withstand higher temperatures (up to 120°C). This level is higher that the temperature used in previous projects (up to 85°C), but this novel proposal could be easily performed by using one of more commercial stainless steel tanks (5,000 liters) that are manufactured at low cost and including all the auxiliary systems needed: two heat exchangers built by copper coils, standard electrical heater, pressure relief valve (3 bar), and good-quality thermal insulation. So, this design exploits the advantage of using low-cost commercial tanks manufactured by Chinese factories, mostly for their solar internal market. We can conclude that this novel proposal could be a "silver bullet" useful in order for this technology can become an affordable and suitable solution.

Up today, this solar+ STES technology remains within the under-developing prototypical level after more than twenty years of studying and a similar number of large-scale projects tested (mostly in German). Moreover, which is worst, I think, is the fact that there are negligible chances of reaching success in the future, since the cost of a huge STES system could hardly become enough cheaper to become a technology economically competitive. Moreover, I think we cannot expect a good prospective for this technology in next years, since also the price of solar collectors seems to have reached a steady level after reaching a large massive production scale. On the other hand, during this period the photovoltaic panels have noticeably become cheaper, as well as other technologies related to the production of electricity and its utilization for heating water, such as 1) the generalization of net metering and distributed generation from homes; 2) the reduced price of battery backup systems, by the hand of the generalization of electric cars that drives the growing up of the second-life battery market; 3) the generalization of air-water heat pumps, which are useful for providing all these low-temperature demands of heat having superlative efficiencies (up to 400%), or conversely, this is equivalent to increase four times the electricity from PV panels.

The vacuum-tube collectors can obtain significant yields during winter, even during cloudy days [29]. Therefore, by using many vacuum-tube collectors the winter demand can be fulfilled working with a short-term STES system. This design is noticeably cheaper than the traditional one based on a huge tank, according to the lower cost of a small tank. Besides, this work will be also studied the thermal and cost performance achieved when this small tank is installed aboveground, instead of the traditional underground siting used in large projects. Hence, it was demonstrated that by using reasonable thermal insulation, the heat losses of the aboveground tank are similar that the underground one, but, since the aboveground tank has an overall cost noticeably lower (up 4 times) than the underground one, the aboveground choice is preferred here.

Finally, this work was a study of the economical optimization of these systems by adding a partial generation of heat from standard electrical heaters. This configuration is reasonable because it could take advantage of using the very low cost "valley" tariff during the night (11 pm to 7 am) for household dwellers.

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