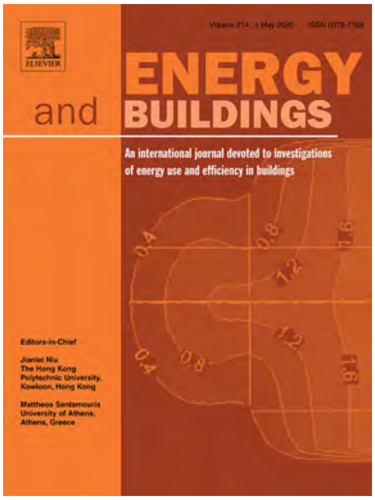

Analysis and optimization of a heat pump system coupled to an installation of PVT panels and a seasonal storage tank on an educational building

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Analysis and optimization of a heat pump system coupled to an installation of PVT panels and a seasonal storage tank on an educational building.

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Abstract

A water-water solar-assisted heat pump (SAHP) is projected on an under construction academic building at the University of Zaragoza (Spain). It integrates a heat pump heating system with photovoltaic/thermal collectors and seasonal storage. Because of its innovative design, considerably higher performances than a conventional type air-source heat pump are expected.

This paper shows the simulation of the system performed in TRNSYS, a graphically based software used to simulate the behavior of transient systems. In addition, starting from the current design of the energy system, different sensibility analysis are simulated in order to study alternative configurations of the heating system. The solar coverage of the current installation design is about 60% and the expected savings yield to a payback period of 15,4 years. Three alternative configurations are proposed in this work, reaching up to around 98% of solar coverage. The study results show the technical and economic feasibility of the heating installation based on a solar assisted heat pump with implementation of seasonal storage in an educational building located in a middle latitude.

Key words

Photovoltaic/thermal hybrid solar panels, Solar assisted heat pump, seasonal storage

Highlights

- Solar assisted heat pump coupled to a seasonal storage is an innovative and efficient solution to provide heat to a building
- Seasonal Storage of thermal energy is technical and economically feasible and it is able to be implemented in a middle latitude.
- PVT panels performance increase with the inclusion in the heating installation of a seasonal storage tank.
- The key sizing factors are the solar field area, the volume of the seasonal storage and the thermal capacity of the heat pump.

Nomenclature

Abbreviations
Coefficient of Performances of the HP (COP)
Domestic Hot Water (DHW)
Heat Pump (HP)
Heating, Ventilation and Air Conditioning (HVAC)
International Energy Agency (IEA)
Internal Rate of Return (IRR)
Levelized Cost of Heat (LCoH)
Net Present Value (NPV)
Pay-Back (PB)
Photovoltaic (PV)
Photovoltaic and Thermal hybrid Panel (PVT)
Solar Assisted Heat Pump (SAHP)
Solar Heating and Cooling (SHC)

Symbols
a_1 Heat loss coefficient (W/m^2K)
a_2 Temperature dependence of the heat loss coefficient (W/m^2K^2)
E_{prod} Electrical production of the PVT panels (kWh/year)
I global solar irradiance(W/m^2)
I_o Initial investment (€)
LCoE Levelized Cost of Electricity (€/kWh)
LOcH Levelized Cost of Heat (€/kWh)
η_o Efficiency (-)
η_{th} Thermal performance of the PVT collectors (-)
N°_PVT Number of PVT panels installed in the project
PB Pay-Back (year)
P_n Peak power of the module (W)
Q_{HP} Heat flow provided by the HP (kWh)
Q_{prod}Thermal production of the PVTpanels(kWh/year)
r discount rate (%)
SF Solar fraction (%)
T period of analysis (year)
Ta Ambient temperature (˚C)
Tc Temperature of the PV cell (˚C)
TC_{HP}Thermal capacity of the heat pump (W)
Tm Average temperature of the fluid in the PVT (˚C)
V_{HS}Volume of the small tank that supports the load side (m^3)
V_{SS}Volume of the Seasonal Storage tank (m^3)
W_{HP} Energy consumption by the HP (kWh)
W_{toGRID} Electricity generated by the PVT panels delivered to other uses (different that HP consumption) (kWh)
$W_{fromGRID}$ Electricity from the grid that assisted the HP consumption (kWh)
W_{PVtoHP} Electricity provided by the PVT panels to the HP (kWh)
W_{PVT} Electricity generated by the PVT system (kWh)
γ Temperature coefficient losses (%/˚C)

Introduction

In 2018 38% of the energy consumption in the European Union is consumed by the domestic and services sectors. Additionally, around 80% of the energy consumption in the residential and tertiary sectors is used to heat water and spaces [1]. Because of this distribution in the use of the energy, the solar thermal energy is an optimal way to produce energy in these sectors. Nevertheless, the highest energy demand in a day occurs in the last hours of the day [2] and at this time, solar radiation does not fall on the solar collectors, so is not possible to directly take advantage the solar thermal energy. Therefore, there is a gap between the daily demand and the energy production. This disorder occurs with the seasonal demand too: the highest space heating demand takes place during the coolest months, but the solar radiation is more powerful in summer.

Daily gap is relatively easy to compensate with the use of water tanks. Seasonal gap is however really difficult to equilibrate and optimize. There are different methods to compensate the seasonal gap. For instance, with the variation of the tilted angle of the collector in winter [3]. Pinel et Al. made a review of the available methods of seasonal storage of solar thermal energy. Storage mechanisms were researched in the frame of the Task 32 of the Solar Heating and Cooling (SHC) programme of the International Energy Agency (IEA) [4]. The storage mechanisms can be classified in three subcategories: chemical, latent and sensible. The most common and economic technology to store energy nowadays is the sensible mechanisms.

Seasonal storage systems are considerably large scale in comparison with daily storage devices. Braun [5] concluded that seasonal storage systems must be between 100 and 1000 times bigger than a daily system per unit of collector area. However, Fish et Al. [6] researched the investment of large storage energy systems and concluded that the invest cost per square meter of solar collectors is only twice the cost of a daily storage system. Construction cost range vary from 50-250 €/m^3 [7] for a water tank of 1000m^3. The invest cost decreases for large scale seasonal storage systems.

According to Braun [8] seasonal storage of solar thermal energy is appropriated to install in high latitude areas on the earth, where the temperature variation during the seasons of the year is high. On the other hand, the southern areas, where solar irradiation is high and there are more light hours, are the suitable places to produce solar energy using photovoltaic and thermal panels [9], there for the installation of seasonal storage mechanisms is recommended too. Further, the buildings where the heating demand is bigger than the domestic hot water (DHW) demand are also right to install this technology.

Sensible storage consists of storing energy as internal energy, by increasing the temperature of a medium, generally solid or liquid. The principal characteristics of a storage medium were research by Hariri and Ward [10]. According to them, the most important requirement of an optimal storage medium is a high thermal capacity. Stratification allows the production of high quality energy when the threshold temperature is met. Stratification allows the effectiveness transmission of heat to the coldest areas of the tank when it is almost fully charged. In the medium selection influence other characteristics like the space limitations, the thermal diffusivity and the cost of it.

Water is the storage medium most employed in space heating and DHW applications [11]. That is because of its characteristics: high thermal capacity (4,184$kJ/kg * K$), non-toxic, non-inflammable, cheap and easy availability. The principal disadvantage of this medium is the operative range of temperatures (20-80 °C), but it does not affect to the mentioned applications. Water is used as storage medium in water tanks, aquifers and solar ponds. The election of the storage technology depends on the characteristics of the project. A.Hesaraki et Al. [12] made an extensive overview about the seasonal thermal energy storage mediums and methods. Hot water tank storage is the most common system and can be built at almost any location. This method allows a high stratification and it is easy to install. Lund [13] researched with water tanks and concluded that stratified storages achieve higher solar fractions than those obtained with fully mixed tanks. Water tanks are made of steel and/or concrete. A limitation of this method are thermal losses. There are different methods that can be used in order to reduce losses. Around the concrete or steel, insulation layers are built to minimize the thermal losses. Another successful method that decreases the thermal loss is to bury the tank, but it has a high cost. Buried tanks have the advantage that can be used in projects with lack of space. This technology can be use in almost any type of soil and climatic conditions [14].

Photovoltaic and Thermal hybrid (PVT) panels are a technology based in the combination of photovoltaics cells and thermal collectors. PVT collectors can produce electrical and thermal energy simultaneously by receiving solar radiation. The overall efficiency of this panels is higher than that of independent photovoltaic (PV) and thermal collectors [15]. Also, the mixed production allows a better adaptation between energy production and demand. Because of the limited space on roof of the buildings, this technology is really attractive to the residential sector. PVT technology has been researched during the last decades. Joshi and Dhoble [16] made an intensive review of the PVT systems and the future trends in this area. They indicate that the materials will take an important role in the optimization of the PVT panels.

PV cells can absorb up to the 80% of the incident solar radiation, however, only a small part of it is converted into electricity [17]. The remaining energy is dissipated as heat. PV cells are semiconductor devices that can convert the solar energy (dispersed and concentrated) into electricity (Direct Current). The electrical efficiency can vary from 6 to 25 % in commercial PV cells depending on the material and the operating conditions [18]. The PV cells performance decreases with the increasing of the operating temperature of it [19]. In order to increase the performance of the PV, and to prevent the deterioration of the cell, is needed the extraction of the heat. In a PVT module, the heat from the cells is extracted by the thermal device and at the same time the panel is producing thermal energy. This system decreases the work temperature of the cells.

The PVT panels can be classified by attending to the work fluid that is used to remove the heat out of them. The heat transfer fluid can be: air, water or a refrigerant. Most of the thermal collectors use water as work fluid, instead of air, because of its higher efficient [20].

Currently, Task 60 of the IEA [21] is focused on the application of PVT collectors in order to assess existing solutions and to develop new system solution principles in which the PVT technology really offers advantages over the classical “side by side installations" of solar thermal collectors and PV modules. Energy production, competitive cost, safety and reliability of systems are being considered within this task.

Solar assisted heat pump (SAHP) is the combination of solar thermal collectors and a single state heat pump (HP). Solar thermal collectors produce thermal energy by the heating of a work fluid. A HP is a thermal machine that transfers heat from a source to another by running a refrigeration cycle. With the increase of the temperature of the cold side of the heat pump the electrical consumption of the thermal machine can decrease. For this reason, the coupling between thermal collectors and a heat pump can increase the overall performance of the system. The heat generated by the solar panels feeds the cold side of the HP, so the electrical energy consumption is lower than if the machine works without the solar system.

Combination of solar thermal collectors and heat pump in a single SAHP system has been used for various purposes including water heating. There exists a growing interest towards most effective use of solar heat pump systems for residential use, as indicated by the IEA the Task 44 of the SHC Program. The Task aimed at optimizing combinations of solar thermal energy and heat pump, primarily for one family houses [22]. That is, one of the items in focus were small-scale residential heating and hot water systems that use heat pumps and any type of solar thermal collectors as the main components.

Coupling of PVT collectors and heat pump presents an additional advantage. The net electrical consumption of energy of the heat pump can be provided by the electrical production of the PVT modules.

During the last decade, there have been numerous contributions regarding SAHP systems for low temperature applications. Bukert [23] carried out a complete and systematic review. Most of the literature refers to conventional solar collectors [24-26], although also the solar hybrid PVT panels are being considered [27-29]. They present important advantages such as the room saving on the roof and the efficiency. PVT technology is also well documented in literature, with interesting studies even in poligeneration scheme [30, 31].

The HP+PVT coupling can be implemented both at small or large scale. A study for heating an industrial building was presented by Del Amo et al. [32], although the seasonal storage was not included. This paper focuses on the case study of a SAHP fed by PVT collectors and including seasonal storage in an academic building at the University of Zaragoza. The final target would be to guide the energy policy towards the large-scale implementation of solar-assisted heat pumps.

Methodology

Although the work presented in this paper is framed within a global refurbishment project including many other energy saving measures, only the aspects directly related to the described energy system were considered.

The project has different work areas. All of these parts have connections between the others and high relevance to achieve a global environmentally and economically efficient installation.

Technical challenge in the use of renewable sources of energy is to match demand and resources along the time. Simple static methods can be used to estimate the dimensions of the installation, but they may lead to significant mistakes and a lack of useful information to operate the system. In order to these limitations, it is useful study the installation with dynamics methods. They are highly recommended when solar resources are involved and allow a better design of solar systems by preliminary dynamic simulation that enhances their viability [33].

The analysis methodology carried out in this work started with the study of the thermal demand for heating in the building. Each component of the energy system was analyzed and sized according to the legal requirements and the correct coupling of the different parts of the generation, storage and consumption sides. In this case of study, because of the placement of the project (Spain), the legal requirements are given by the *Código Técnico de la Edificación* (CTE) [34] and the *Reglamento de Instalaciones Térmicas en los edificios* (RITE) [35]

Demand profiles were calculated in DesignBuilder, a powerful software to simulate the energetic behavior of buildings [36]. It allows the representation of building envelope, uses of the different areas, occupancy and the thermal requirements. Then, the profiles of the thermal demands in the building were obtained. Results were evaluated to check their consistency with the demand ratios declared in the approved project of the building.

Besides the demand, the climatic data where obtained from an external software, Meteonorm [37], after evaluating and contrasting different data sources: PVGIS [38], NASA [39], National Databases [40].

The model of the installation was elaborated in TRNSYS [41], a reference transient systems simulation software with modular structure, mainly applied on renewable energy systems analysis. It also includes libraries for low energy buildings, HVAC systems, cogeneration and fuel cells. Additionally, many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. Since solar systems are highly dependent of the passage of time, TRNSYS is well suited to detailed analyses of them [42]. Furthermore, weather and climatic data of the placement of the building were introduced in the model, as well as the demand profile. These data are input elements of the model.

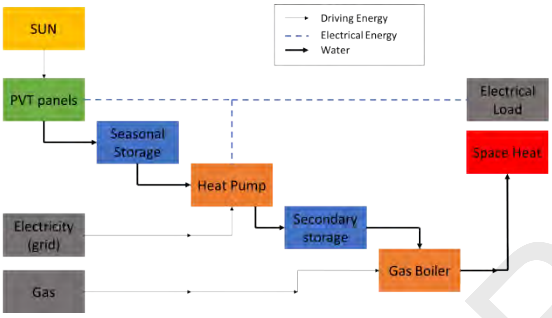

Figure 1. Visualization of the PVT system.

A coupled operation of a PVT solar field and a water-water heat pump present relevant advantages. However, the specificities of both components must be considered in order to meet the optimum coupling. On the one hand, the performance of the PVT panels is better as lower is their operating temperature: thermal efficiency is higher because the convection losses considerably decrease and so is the electrical efficiency, since the cell temperature is lower. On the other hand, the behavior of the heat pump improves with high temperature in the cold side because the compressors consumption is lower. Therefore, there exists an optimum operating point in the coupling. Such a point is not easy to determine since it requires an annual simulation to analyze the temperature of the three-way valve that maximizes production by modifying the inlet water temperature on the condenser. This study requires the dynamic simulation carried out in this work.

The heat pump provides the heat flow (Q_{HP}) feeding the heating circuit of the building. The electricity flow demanded by the HP (W_{HP}) depends on the system operation at each step; the temperatures of the evaporator and of the condenser are the key variables. Clearly, the different operation characteristics of the heat pump are provided by the manufacturer and introduced in the simulation.

The electricity provided by the PVT panels feeds the HP (W_{PVtoHP}). At each step of time, it may happen that the production W_{PVT} was higher or lower than the HP electricity demand. Then, if W_{PVT} exceeds W_{PVtoHP}, the extra electricity is delivered to other electricity consumers in the building and this amount of energy is denoted as W_{toGRID}. It may alternatively happen the opposite situation: the variable $W_{fromGRID}$ is therefore defined when the electricity produced by the solar field is not enough to instantly feed the heat pump. To sum up, two basic electrical energy balances are stated accordingly:

$$W_{PVT} = W_{PVtoHP} + W_{toGRID} \quad (1)$$

$$W_{HP} = W_{PVtoHP} + W_{fromGRID} \quad (2)$$

Equation (1) indicates that the electricity production of the PVT panels meets the HP electricity demand and may eventually feed other demands as well. Equation (2) is focused on the HP electricity demand and states that it is covered by the photovoltaic production in the PVT devices and, if required, taken from the network. The contracted power in the building is considerably higher than the peak PV production, so the total electricity produced in situ is assumed to be consumed.

The background analysis of the system is based on the basic performance equations of its main component: the heat pump and the PVT panels. The HP is operating in heating mode, demanding electrical energy to run the mechanical compressor and providing a heat source at high temperature to produce domestic hot water. The coefficient of performance of the heat pump is a measurement of its efficiency (Equation 3) [43].

$$COP = \frac{Q_{HP}}{W_{HP}} \quad (3)$$

The PVT panels produce simultaneously heat and electricity according to the specifications provided by the manufacturer. The thermal performance is defined by the panel thermal yield and the design of the system. The instantaneous efficiency varies with the operating conditions according to Equation (4):

$$\eta_{th} = \eta_0 - a_1 * G - a_2 * G * (T_m - T_a) \quad (4)$$

Where η_o is the efficiency, a_1 is the heat loss coefficient, a_2 is the temperature dependence of the heat loss coefficient, Ta is the ambient temperature, Tm is defined as the average temperature between the input and output temperatures and $G = (T_m - T_a)/I$ where I is the global solar irradiance.

The electricity production of the PV cells encapsulated in the PVT panel depends on the solar irradiation and the cell temperature Tc, as well as on the physical features of the photovoltaic material. Equation (5) determines the power delivered by the PV modules considering the peak power of the module (P_n), the solar irradiance (I), the temperature coefficient losses (γ) and the cell temperature (T_c).

$$W_{PVT} = P_n \cdot \frac{I}{1000} \cdot [1 - \gamma \cdot (T_c - 25)] \quad (5)$$

The cell temperature is directly connected to the temperature of the absorber plate, that is, to the temperature of the flow going in and out of the panel. This is a fundamental difference between the conventional PV modules and the PVT ones, since the temperature at which the cell is operating is determined by the flow in the solar circuit.

The solar coverage is calculated by comparing the heat produced by the solar field, excluding the losses in pipes and storage, to the demand of the building. Solar coverage of the HP refers to the amount of electricity produced by the hybrid panels that feeds the heat pump. This ratio is calculated by comparing W_{PVtoHP} by the electricity consumption of the HP (W_{HP}).

The most important parameters that define the behavior of the installation are: the collector area, the thermal capacity of the HP, the volume of the seasonal storage tank and the volume of the hot side tank of the HP. With the variation of these four parameters it is possible to improve the global performance of the heating system.

This paper includes a sensitivity analysis of the installation with the purpose of making a proposition of an installation that behaves better, in energetic and economical terms, than the installation of the case study. In order to achieve this objective, three different cases have been studied.

Economic analysis is highly relevance because the installation should be efficient and respectful with the environment and profitable as well. Total investment is the initial cost of the installation. This cost includes the technology and the setting up. The Net Present Value (NPV) is a method that indicates the difference between the actual value of the flow of inlet cash and the flow of outlet cash over a period of time. When the NPV has positive value, it indicates that the investment is recommended. The Internal Rate of Return (IRR) represents the rate that makes the NPV equal to zero. The investment is recommended when the IRR has a value greater than another set (reasonable return). It indicates the profitability rate of the project. The Payback time (PB) represents the period of time elapsed before an investment is recouped. It is calculated as the ratio between the investment and the yearly cash flow. In this study PB has been calculated linearly. The estimated lifetime of the studied installation is 25 years. The interest rate that has been considered to calculate economical ratios is 4%.

The Levelized Costs of Heat (LCoH) and the Levelized Costs of Electricity (LCoE) are economic indicators based on the concept of levelized cost of energy[44] and they are calculated according to Equations (6) and (7) [45]; it was developed in the frame of the Task 60 of the IEA [21].

$$LCOH = \frac{\left[I_0 + \sum_{t=1}^{T=25} OM_t \cdot (1+r)^{-t}\right]_{HS}}{\sum_{t=1}^{T=25} Q_{PVT} \cdot (1+r)^{-t}} \quad (6)$$

$$LCOE = \frac{\left[I_0 + \sum_{t=1}^{T=25} (OM_t) \cdot (1+r)^{-t}\right]_{ES}}{\sum_{t=1}^{T=25} E_{PVT} \cdot (1+r)^{-t}} \quad (7)$$

Where I_o is the initial investment, OM_t is the maintenance cost of the installation, Q_{PVT} is the thermal production of the PVT panels, E_{PVT} is the electrical production of the PVT panels, r is the discount rate and T is the period of analysis. The maintenance cost can be considered as a 1-2% of the investment cost of the project [46, 47]. In this case, maintenance cost is calculated as the 1% of the investment cost. This provision will meet the maintenance cost, such as the replacements of the inverter and the heat pump or any other component. The investment cost results interesting in the case that the LCoH and LCoE have value under the reference cost of the energy. The electricity and gas cost in Spain for a building with high demand can be considered 0,1458 €/kWh and 0,0490 €/kWh respectively [48].

Case study

The SAHP is currently being installed on an academic building at the University of Zaragoza. The different rooms are organized in three floors, with a total surface of 6700 m², comprising classrooms, meeting rooms, offices, central floor and corridors, auxiliary spaces… The solar system comprises 75 PVT panels and 200 conventional PV panels (Fig. 3), with a seasonal storage of 300 m³.The system is devoted to provide heating for the building and the PV production is expected to be self-consumed both by the HP and the other electrical demands of the facility. There are additional operation strategies to meet the heat demand when the storage runs out. Heat pump may operate with geothermal.

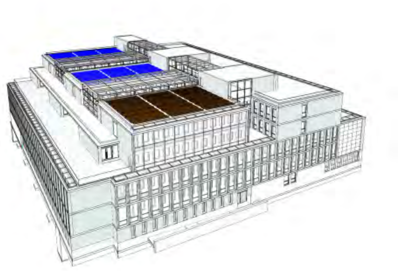

Figure 2. Location of the PVT (brown) and PV panels (blue) on the roof of the building.

The hybrid solar field, south-faced and with a slope of 37º, is composed by aH-72 panels (1.96 m^2 total area), manufactured in Zaragoza by Abora Solar [49]. Each panel has a rated power of 350 W_p with 72 PV cells; the thermal specifications are: 0.7 for the efficiency and 5.78 W/m^2K and 0.00 W/m^2K^2 for the coefficients of thermal losses, a_1 and a_2 respectively. The performance provided by the manufacturer is shown in Figure 4, where T_m is the average temperature of the fluid in the collector, T_a is the environment temperature and G is the solar irradiance.

The solar circuit includes an air heater that dissipates the surplus of heat from the outlet flow from the PVT. This heat sink has been installed because of safety reasons. Although, a good operation of the system will lead to hardly use of heat dissipation.

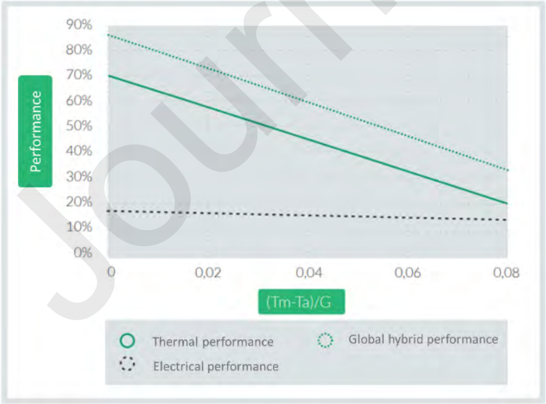

Figure 3. Performance of the hybrid panel aH-72 (source: Abora Solar [49]).

The 300 m^3 storage tank is buried just below the main hall of the building and stores the surplus of solar energy collected by the panels. It has been made in polyester fiberglass (0,035 W/m*K) with an insulation of 200 mm of high-density polyurethane (0,028 W/m*K) and external jacketed. The thermal transmittance of the seasonal storage tank is around 0,128 W/m^2K. It constitutes de cold side in the operation of the 29 kW_t water-water heat pump which is included in the project. The projected HP that will be installed is the model 61WG-020-090 from Carrier [50]. The HP is operating in heating mode. According to the manufacturer, the inlet flow to the HP from the cold side must be in the range of temperatures between 5 and 27 $^\circ C$ and the temperatures of the inlet flow from the hot side to the HP in range between 20 and 65 $^\circ C$ [51]. These restrictions may prevent the malfunction of the machine. If the temperature of the inlet water flows is not between the minimum and maximum values, the HP will switch off automatically. There exists a small back up hot storage tank of 10 m^3 to support the consumption side that constitutes the hot side of the HP.

The heating option for the building is an air-based duct system. It provides heating in a room from the top for consistent, efficient warmth and silence. Figure 4 presents the heating demand profile in the building along the year. The building yearly demands 114.750 kWh for heating.

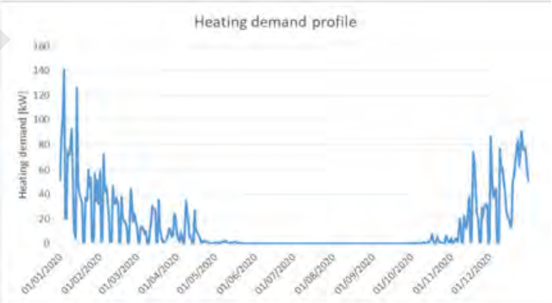

Figure 4. Heating demand profile in the building calculated with the software DesignBuilder.

Invest cost can be divided in the two main blocks that constitutes the installation: the seasonal storage tank and the SAHP system that includes the HP and the solar field of PVT panels. The cost of the seasonal storage tank is around 350 $€/m^3$. The installation of the SAHP cost is estimated in 87.255€. The total investment cost of the installation is 192.255 €.

Results and discussion

First, the case study installation was studied and analyzed. The characteristic data of the installation are included in Table 1. Solar irradiance on the panels is 1.794 $kWh/m^2/yr$. It means that the total raw solar energy input on the system is about 263.718 kWh/yr. Since the thermal and electrical production of the PVT field are 79.452 and 37.972 kWh/yr. respectively. Thermal yield rises up to 30.1% while electrical yield reaches 14.9%.

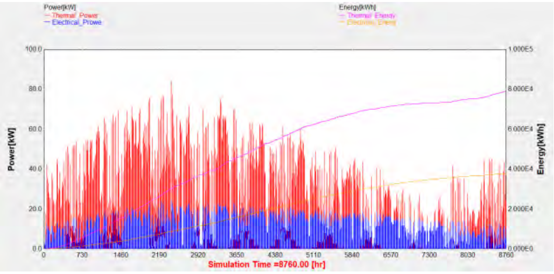

Figure 5. Thermal and electrical power and energy production of the PVT.

Because of the size of the seasonal storage tank, the thermal performance of the PVT is not as good as it would be if the tank were bigger. Each panel of this model of PVT collectors is able to achieve a thermal production of 2.000 kWh/year (from 10°C to 85 °C) considering the same weather conditions take place in the studied project and in case that all the produced heat was consumed in form of DHW. In the case studied, the thermal production of each panel has a value of 1.059 kWh/year. Thermal power production in summer is lower than in winter (Figure 5). That is not the expected result. This response occurs because of the small size of the seasonal storage tank. In summer, the tank is empty and it is not possible to store more energy inside it. In addition, a high inlet temperature in the PVT panels reduces the thermal and electrical performance of them, because of the increment in the work temperature of the panels. In conclusion, the potential of the PVT collectors is being exploited. In order to prove the hypothesis that says that the thermal production of the PVT panels does not match the maximum values due to the size of the seasonal storage tank it has been evaluated (Figure 6) the evolution of the thermal and electrical production of the PVT panels with the increase of the volume of this tank.

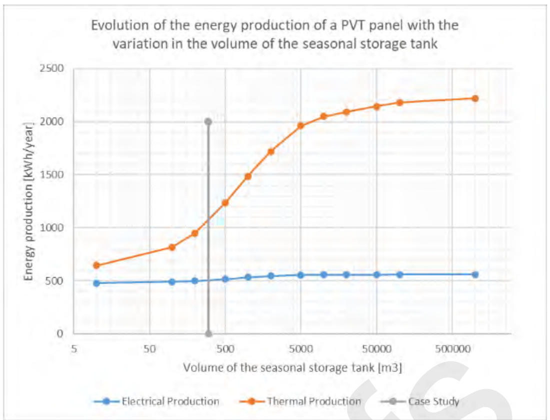

Figure 6. Evolution of the thermal production of a PVT panel with the variation in the volume of the seasonal storage tank.

The evolution of the temperatures within the seasonal storage (top and bottom of the deposit) can be observed in Figure 7. Temperature of the storage ranges from 2,5 to 75 $^\circ C$, what means an amplitude of 72,5 $^\circ C$. The temperature of the top of the tank does not take the maximum value of 85 $^\circ C$ fixed in order to preserve the safety in the installation. That means that the air heater does not be activated. The charge (summer) and discharge (winter) periods can be easily identified: charging period starts in spring, when there already exists a surplus of the production of thermal energy versus the heating demand.

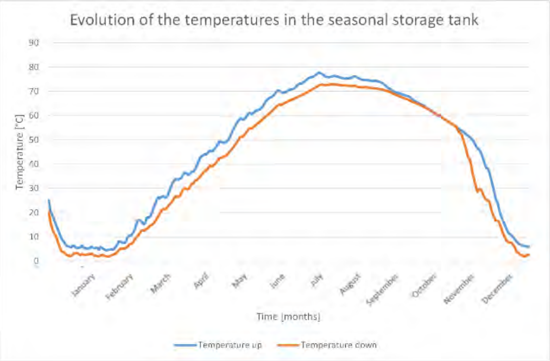

Figure 7. Evolution of the temperatures in the 300 m^3 seasonal storage tank.

The 95% of the electricity produced by the PVT field leaves the inverter as alternating current to feds the HP (4.994 kWh/yr.) as well as any other electrical requirements of the building or being delivered to the grid (31.086 kWh/yr.). As a whole, 13,8 % of the renewable electricity produced by the system is directly consumed by the HP. It means the 28,6 % of the electricity demand of the HP.

Figure 8 shows the production of electrical energy of the PVT panels during a year. As well as the distribution of this energy. It can be seen that during the summer nothing of the electrical production is consumed by the HP, because the HP does not work. Absorbed and transferred thermal energy by the HP and the electrical consumption of it is also shown in Figure 8. The production of heat is higher than the heat that is consumed from the cold side. Therefore, the HP is working properly. The total electrical consumption of the HP in a year is less than the total production of energy of the PVT collectors, but the consumption of renewable energy of the HP is not the 100%. That occurs because when it is needed power in the HP the collectors are not generating it.

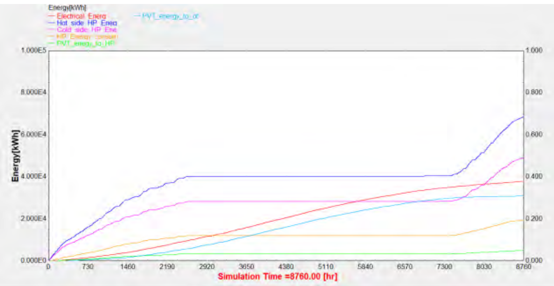

Figure 8. Distribution and consumption of energy in the installation.

The solar coverage rate, that is, the percentage of the amount of energy for heating that is provided by the sun is 59,9%.

Considering the expected savings, it yields to a payback period of 15,4 years. Moreover, NPV for 25 years is 6.891,85 € and IRR esteems a profitability in the investment of 4,1%. Levelized Cost of Heat (LCoH) in this project will be 0,0114 €/kWh and the Levelized Cost of Electricity (LCoE) is 0,0252 €/kWh.

In order to improve the heating installation, a sensitivity analysis was performed. The study consisted of the energetic analysis of the installation with the parametric variation of the principal variables that describe it.

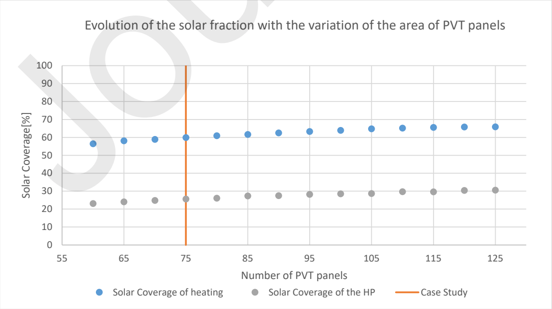

Figure 9. Evolution of the solar fraction of heating and of the HP with the variation in the collection area.

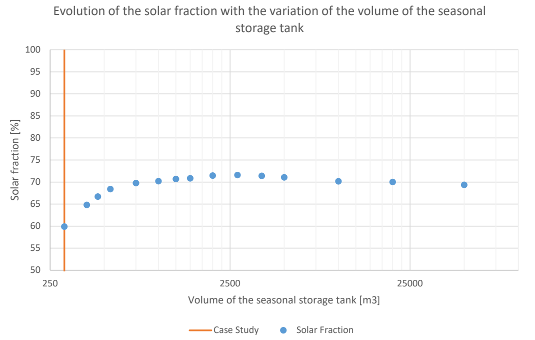

Figure 10. Evolution of the solar fraction with the variation of the volume of the seasonal storage tank.

In the study of the behavior of the solar fraction with the variation of the number of PVT panels (Figure 9), it is observed that the solar fraction of the heating installation increases with the increment in the number of hybrid collectors until the solar fraction achieve a maximum in 65,9 % and then it remains constant. This behavior is explained because the increment in the collection area results in the increase of the amount of heat produced by solar energy, and therefor in the production of heat of the global installation. The solar fraction remains constant when the number of PVT panels that are installed is minimum 115. For the reason that the performance of the hybrid collectors decreases with a high operation temperature and that the insufficient volume of the seasonal storage tank promotes the increase of the average temperature in the PVT panels, the installation can not be improve only with an increase in the number of panels. The same behavior has the solar coverage of the HP, it increases with the increment in the number of PVT collector until a maximum of 29,7%. The evolution in this ratio is explained because the seasonal storage volume remains constant and with the incrementation in the collection area it is produced an increment in the work temperature of the PVT panels. Thus, proves that the increment in the work temperature of the panels reduces the electrical performance of them.

Analysis of the evolution solar fraction with the variation of the volume in the seasonal storage (Figure 10) shows a similar behavior than the observed with the variation of the PVT panels. The highest solar fraction achieved is 71,6% that occurs with a seasonal volume of 2750 m^3. In one hand, for seasonal storage tanks with a volume lower than the optimum, the PVT panels do not work at their total capacity because a small tank causes a high operation temperature in the primary circuit. And in the other hand, when the installed seasonal storage tank is bigger than the optimum, solar fraction remains constant or even decreases because the PVT panels are producing at their highest capacity but the average temperature of the seasonal storage tank, that is the low temperature side of the HP, is too low.

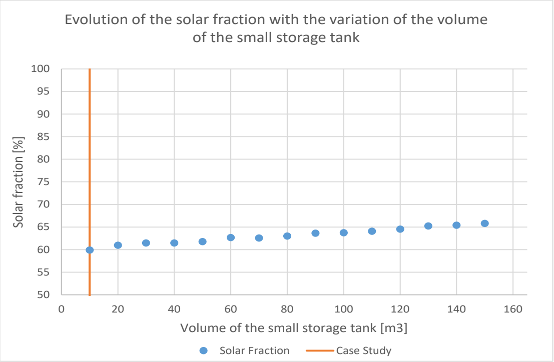

Figure 11. Evolution of the solar fraction with the variation of the volume of the small storage tank (hot side of the HP).

Figure 11 shows an increasing evolution of the solar fraction with the increment of the volume of the small hot tank that supports the demand of the building. Solar fraction takes a stable value since the volume reaches 120 m3. The small tank should be bigger in order to improve the global performance of the heating installation.

The change in the thermal nominal capacity of the heat pump can also increase the potential of the SAHP with seasonal storage system (Figure 12). Optimal duty point of the HP is a nominal thermal capacity of 38 $kW_{t.}$

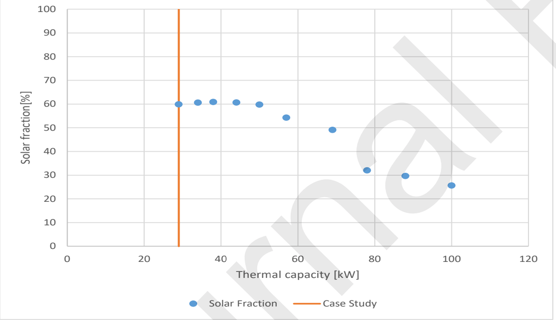

Figure 12. Evolution of the solar fraction with the variation of the thermal capacity of the heat pump.

With the objective of studies the potential of the low temperature thermal emitters, a parametric analysis of the behavior of the solar fraction of the installation with the variation of the operative temperature of the heating unit was performed. The results can be observed in Figure 13, which shows the low solar fraction achieved in the installation with the increment in the operative temperature of the heating system. The constant behavior of the solar fraction with the variation of the operative temperature in the range 30-65 °C is because the upper limit temperature of the heat pump is 65 °C. When the operative temperature of the heating system is higher than 65°C the supplied heat that can not be produced by the heat pump is delivered by the gas boiler consequently the solar coverage decreases.

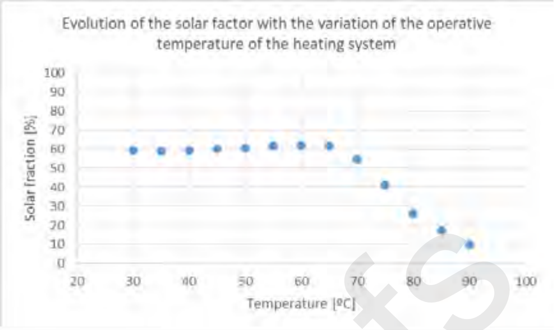

Figure 13. Evolution of the solar fraction with the variation of the operative temperature of the heating system.

As it has been shown in Figure 5, the seasonal storage tank should be bigger in order to improve the performance of the PVT panels. Another option to achieve a better response of the PVT collectors is to reduce the number of them. That is because with a small seasonal storage tank the amount of thermal energy that can be stored in it is limited. The challenge is to equilibrate the thermal production of heat by the PVT panels and the thermal storage capacity of the seasonal storage tank.

In Figure 14 it can be observed how the heating ratio of the studied building can influence on the solar coverage of the heating installation. In order to have high solar fractions it is needed a quality building envelope that contributes to the reduction of the heating demand of the construction.

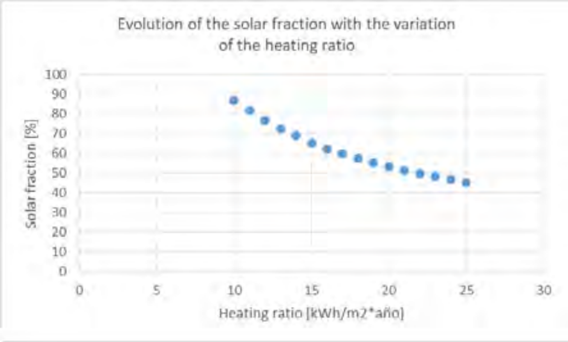

Figure 14. Evolution of the solar fraction with the variation of the heating demand ratio of the building.

In order to improve the behavior of the heating system, three parametric studies. have been made The first one studies the variation of the solar coverage of the installation with the simultaneous variation of the number of PVT panels and the thermal capacity of the HP (Figure 15). The other studies the variation of the solar coverage with the simultaneous variation of the volume of the seasonal storage tank and the nominal thermal capacity of the

HP (Figure 16). The last parametric study shows the evolution of the solar fraction of the installation with the simultaneous variation of the volume of the seasonal storage tank and the small tank (load side). This study is implemented with a HP with a nominal thermal capacity of 57 kW$_t$ and 75 PVT collectors (Figure 18). The U-value of the seasonal storage tank has remained constant in all the simulations.

As it can be seen in the Figure 15, the solar coverage has the maximum values with the implementation of a HP with a thermal capacity of 38 kW$_{t.}$ The optimal number of PVT panels is 135. With this installation (Case 1) the solar fraction will be 71,2%.

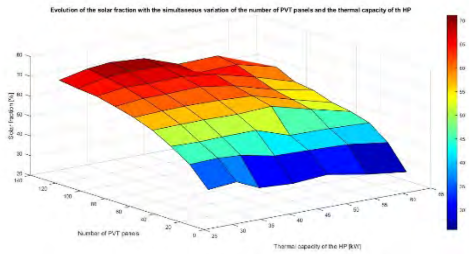

Figure 15. Solar fraction of the installation with the simultaneous variation of the number of PVT panels and the thermal capacity of the HP.

The second parametric study shows an optimal working point of the seasonal storage tank of 1500 m^3. The installation with a HP of 57 W and a seasonal storage tank with a volume of 1500 m^3 (remaining the rest of parameters equal to the base installation) will achieve a global solar coverage of 94,7 % (Case 2).

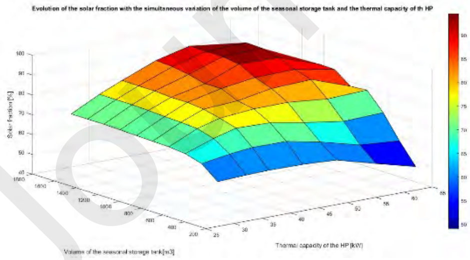

Figure 16. Solar fraction of the installation with the simultaneous variation of the volume of the seasonal storage tank and the thermal capacity of the HP.

The optimization of the volume of the seasonal storage tank not only increases the solar coverage, but also enhances the thermal performance of the PVT panels (Figure 17).

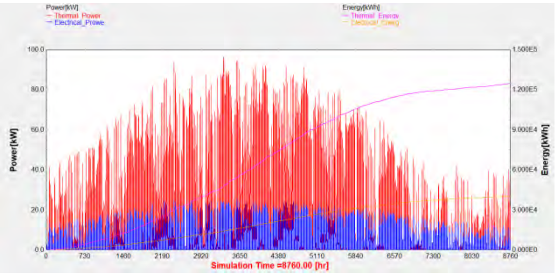

Figure 17. Thermal and electrical power and energy production of the PVT with a seasonal tank of 1.500 m^3 and a thermal capacity of the HP of 57 W$_t$.

	Base Case	Case 1	Case 2	Case 3
V_{HS} [m^3]	10	10	10	15
V_{SS} [m^3]	300	300	1500	1500
Nº_PVT	75	135	75	75
TC_{HP} [W$_t$]	29	38	57	57
SF[%]	59,9	71,2	94,7	97,7
Q_{prod} [kWh/year]	79452	100871	125167	125949
E_{prod} [kWh/year]	36080	65839	40627	40647
PB [year]	15,4	20,7	17,8	18,1

Table 1. Characteristic parameters of the studied cases in the first year of use of the installation.

As it has been displayed in Figure 12, the increment in the volume of the small tank that supports the load side of the installation increases the solar fraction of the installation. This situation is studied in the third parametric study with the variation of the seasonal storage tank simultaneously.

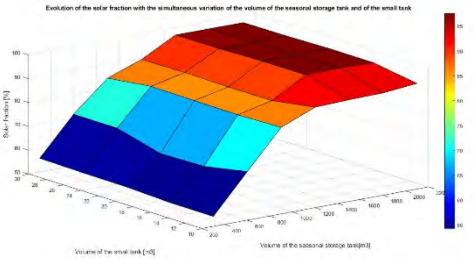

Figure 18. Solar fraction of the installation with the simultaneous variation of the volume of the seasonal storage tank and the small tank.

Figure 18 shows that it is possible to increase the solar coverage with an increment of the small tank as well as with the increase of the seasonal storage tank. This situation can be used to achieve an efficient installation with less seasonal storage volume. That makes the installation economically efficient as well, because the investment cost of the seasonal storage tank is the highest cost of the installation. Therefore, a third case (Case 3) was suggested. This installation is composed for a seasonal storage tank of 1500 m^3 and a small tank in the hot side of the HP of 15 m^3. The global solar coverage in Case 3 is 97,7 %. In this case, the increment in the hot side tank volume does not result in a reduction in the volume of the seasonal storage tank.

	Base Case	Case 1	Case 2	Case 3	Ref. price
LCoH [cent€/kWh]	1,14	1,88	0,73	0,72	4,90
LCoE [€/kWh]	2,25	2,88	2,23	2,23	14,58

Table 2. Levelized Cost of Energy (Heat and Electricity) of the studied cases of the installation.

Conclusions

The study results show the technical and economic feasibility of the heating installation based on solar assisted heat pump with implementation of seasonal storage in an educational building located in a middle latitude because of the saving that occurs with the employment of renewable energy source. Due to construction reasons the initial configuration of the installation is not completely optimal from the perspective of the coverage of heating demand with renewable energy source. However, investment cost of the project must be considered. This paper shows that the installation of some technologies, like seasonal storage tank, involve an increase in initial investment (Case2).

The use of PVT collectors in the installation with a seasonal storage tank produces an increase in the global performance of the hybrid panels because of the reduction in the work temperature of them. Moreover, PVT panels produce thermal and electrical energy through the installation of a single device. That implies an advantage in buildings with roof space limitations. Seasonal storage of thermal energy coupled to a heat pump increases the seasonal performance of the thermal machine, for the reason that the increase of the temperature of the cold side of the heat pump involves a reduction in the electrical consumption of it. In addition, the electrical production of the PVT panels is used to cover the demand of energy of the heat pump. This fact promotes the self-consumption of the installation.

The optimization of the thermal envelope of the building and the implementation of low temperature thermal emitters are key factors in order to achieve economical and energetic savings with the implementation of this type of installation.

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Table 1. Characteristic parameters of the studied cases in the first year of use of the installation.

	Base Case	Case 1	Case 2	Case 3
V_{HS} [m^3]	10	10	10	15
V_{SS} [m^3]	300	300	1500	1500
Nº_PVT	75	135	75	75
TC_{HP} [W$_t$]	29	38	57	57
SF[%]	59,9	71,2	94,7	97,7
Q_{prod} [kWh/year]	79452	100871	125167	125949
E_{prod} [kWh/year]	36080	65839	40627	40647
PB [year]	15,4	20,7	17,8	18,1

Table 2. Levelized Cost of Energy (Heat and Electricity) of the studied cases of the installation.

	Base Case	Case 1	Case 2	Case 3	Ref. price
LCoH [cent€/kWh]	1,14	1,88	0,73	0,72	4,90
LCoE [€/kWh]	2,25	2,88	2,23	2,23	14,58

Author Statement

Alejandro del Amo: Conceptualization, Methodology, Software, Validation, Writing-Review and Editing

Amaya Martínez Gracia: Methodology, Validation, Writing-Review and Editing, Supervision

Teresa Pintanel: Software, Writing-Original Draft, Visualization
Ángel Bayod Rújula: Methodology, Validation,
Sergio Torné: Conceptualization, Original data of the case study.

Highlights

- Solar assisted heat pump coupled to a seasonal storage is an innovative and efficient solution to provide heat to a building
- Seasonal Storage of thermal energy is technical and economically feasible and it is able to be implemented in a middle latitude.
- PVT panels performance increase with the inclusion in the heating installation of a seasonal storage tank.
- The key sizing factors are the solar field area, the volume of the seasonal storage and the thermal capacity of the heat pump.