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HEAT PUMP FOR RADIANT COOLED AND HEATED FLOOR DRIVEN BY A MICROPHOTOVOLTAIC SYSTEM

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ABSTRACT

This paper reports a solar trigeneration system installed at the Solar Energy Experimental Plant owned by the Spanish National Research Council (CSIC), located in Arganda del Rey, 20km east from Madrid.

The trigeneration system is composed of a 21m^2 Pv polycrystalline (180Wp) collector field, and a 27,5m^2 radiant floor laboratory. The Pv system stores electrical energy in 250Ah batteries that is converted from DC to AC through a 3.0 kW inverter that feeds a reversible air-water mechanical compression, 5-6 kW cooling-heating capacity, heat pump.

The facility was put into operation at the end of August 2012 and it worked until 24 of September, 2012. During this period, the heat pump worked in cooling mode, supplying around 770 l/h flow of a water-etilenglicol (10%) solution to the radiant cooled floor with a minimum working temperature of 7ºC. At the last of November the system started the heating mode that will continue until April 2013. During this period the values will be measured and analysed.

A data storing system was used to record measurable variables such as solar radiation at the Pv field surface; outdoor temperature; input power into the batteries; Pv collectors' efficiency; electrical energy conversion DC/AC; thermal load and calorific demand; cooling and heating power generated; heat flow absorbed by the cooled floor; heat pump's COP, indoor temperature and system's working hours.

The objective of this work is to present and discuss the experimental results of the trigeneration system during 28 days of the summer and one representative day of winter season.

Keywords:Micro-Generation,Solar Trigeneration, Solar PV, Cooling/Heating; Radiant floor.

INTRODUCTION

It's well-known the interest that solar energy photovoltaic conversion has generated since the decade of 1970. As a consequence of scientific activity this technology has experienced a remarkable development which can be seen in the increasing number of this type of installations all over the world. The acceptance of photovoltaic systems has spread due to its easy installation, to being a producer of a clean way of energy like electricity and the institutional support, which results in an economic support.

Unfortunately, as a consequence of the economic crisis that EU is suffering, this support is being questioned in some countries, like Spain [1], where subventions have been recently reduced. Legal system is also changing and specifically in Spain in a few months the concept of 'net balance' will be implemented trying to boost the 'auto-consumption' [2] which improves the consumption of photovoltaic electricity in buildings and houses. This tries to avoid as much as possible the use of the electrical supply for the exportation by small consumers.

Consequences of this change in legislation are already palpable even before its publication. First of these consequences is the fact that solar systems of lower power are demanded, which implies that the economic investment will also be lower. This fact is having a positive influence because the number of installations is increasing. This increase in the demand has also to do with the competitiveness in the industry that produces the main component: the photovoltaic unit. In accordance with the information supplied by the European Photovoltaic Industry Association (EPIA) the cost of the photovoltaic watt has experienced a remarkable descent, reducing up to 25%

between 2000 and 2011, as figure 1 shows, according to [3].

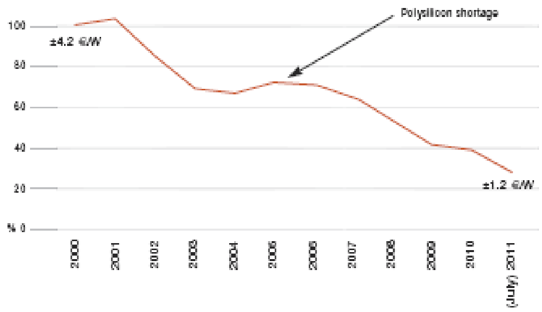

Figure 1. Evolution of the average Pv module price in Europe.

The second of these consequences, which will probably be shown in the future, but which is already being noticeable, is that the development of small power systems is related to the use of electricity for the consumption of lighting and small electrical appliances. However, the use of photovoltaic energy for some other uses like space heating and cooling in houses and buildings may suffer a recession because they use systems that require bigger areas. Precisely this inconvenience may act as an incentive to increase the efforts in finding ways to use photovoltaic electricity for heating and cooling.

This interest is shown in the investigations that have been recently published, like Castro et al. [4], Jukka et al. [5], Hartmann et al. [6], Kohlenbach et al. [7] and also Xiu et al, [8], among others. Hartmann has developed a theoretical model that studies the air-conditioning of two small offices in two different buildings: one in Freiburg and another one in Madrid. In his work he compares the profitability of using thermal and photovoltaic conversion for heating and cooling. He concludes that the photovoltaic system is the most profitable and that fact will make it the system to be chosen in the future. That is also the conclusion reached for Kohlenbach et al. The aim of Xiu's work is developing a photovoltaic system to fed a membranes system to be used in the production of cold with LiBr-Water solutions absorption cooling machines.

The authors of this work are included in the investigation topic "Saving Energy and Emissions Reductions in Buildings", which carries out their work at the Solar Energy Experimental Plant owned by the Spanish National Research Council (CSIC), located in Arganda del Rey, 20km east from Madrid. Between years 2011 and 2013 they have been developing the investigation project: "Design, construction and experimental assessment of a high performance, solar-powered air conditioning and tri-generation system for buildings and greenhouses (ENE2010-20650-CO2-01)", whose objective is substituting fluorinated refrigerants (R22, R410A, etc) in the air conditioning systems.

This group is focused on the investigation of heating and cooling systems that use thermal and photovoltaic conversion of solar energy: development and construction of highly efficient air condensed LiBr-Water absorption cooling machines, and in the case of photovoltaic conversion on the production of cold and heat with a vapor mechanical compression (conventional) heat pump system.

The work we show is related to our photovoltaic activity. Below we show the details of the installation and some experimental results gotten during the summer and autumn of 2012 are included.

THE SYSTEM

It is composed by five subsystems: the weather station; the building to be acclimatized; the photovoltaic field with its own storage system; the conventional heat pump; and the heated/cooled radiant floor.

The weather station: environmental variables

Figure 2 shows the sunlight for two different typical clear summer days in Madrid: 28/08/2012 and 06/09/2012. The maximum solar radiation, for both days, is over 1050 W/m^2. Figure 3 presents the outside dry bulb temperature. The minimum temperature was 17.0 °C while the maximum for the 28th August was 35 °C.

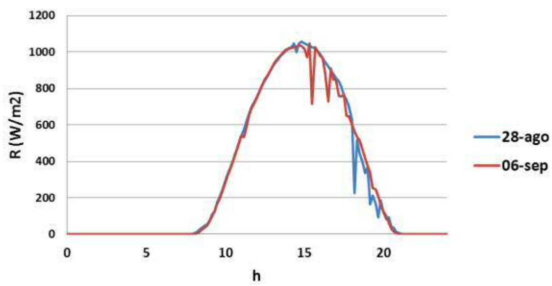

Figure 2. Solar radiation.

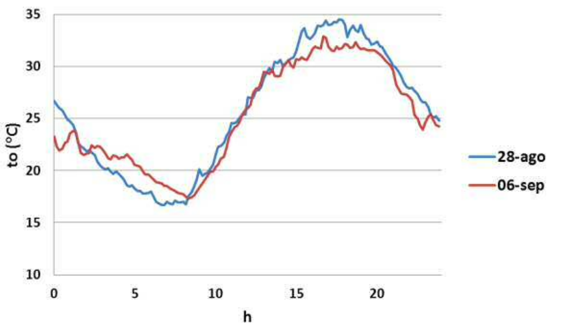

Figure 3. Outdoor temperature.

The building

It is a thermal laboratory that is used as a prototype for the study of heating/cooling systems with photovoltaic electricity as the main energy source. It has a built area of 27.5 m^2 divided into two internal rooms: one of them housing the storage system, the inverter, the Maximum Power Point Tracking (MPTT) controller and the measurement and control system. The laboratory is usually occupied by three people using the other one room.

The building has been built accordance with the 2006 "Código Técnico de la Edificación (CTE)" [9]. Its main thermal characteristics in stationary state are the following: UA = 150 W /°C and internal loads Q_i = 1.2 kW. The maximum thermal cooling load is Q_{lmx} = 3.5 kW, while the thermal heating load is about 4.0-5.0 kW, that can reaches a peak about 6.0 kW in the starting when the thermal inertia of the building is more important.

The photovoltaic field

The field consists of 16 modules (18.7 m^2 useful surface of panels) occupying a total area of 21 m^2. Each module is composed of 48 polycrystalline silicon cells of 0.156 m x 0.156 m, and can generate a nominal power of 180 W, being the total nominal power installed 2.9 kW.

Figure 4. Photovoltaic field and building.

The tilt angle of the modules measured from the horizontal is 40º. Those panels are connected between them in a way that the array can generates a total DC electrical output of 48 V of potential difference.

This electricity is driven to the laboratory, showed in Figures 4 and 5, where the MPPT is installed and controls the operation of this electric field supplying it into the storage system compose of two batteries of 250Ah, where it is kept to be used.

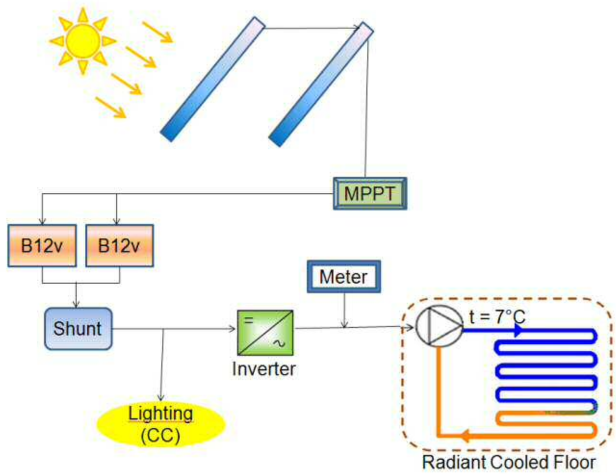

Figure 5. Cooling diagram flow.

This electricity can be used directly as DC power for lighting. This application is not the objective of research and, therefore, is conducted only in exceptional cases. The inverter with an output of 3.0 kW, not optimized yet [10] and [11], converts DC into AC power and supplies it to the heat pump.

The heat pump

It is a reversible air-water mechanical compression, 5-6 kW cooling-heating capacity, heat pump [12] driven by an inverter system, Figure 6. During the summer season, the outdoor unit is condensed by air. The evaporator (indoor unit) is an indirect system that uses water as a secondary refrigerant. The water circulates into a closed loop system situated under the floor (radiant floor), Figure 7, collecting heat from the building and driving it to the evaporator, where the water is cooled, removing, via this process, the heat demand of the building. The heat pump can be driven by Pv electricity or, if necessary, by the electrical grid.

The cooled and heated floor

The radiant floor has an area of 24 m^2 and is divided into two circuits in order to supply heat or cool to each of the two rooms in which the laboratory is divided: one is used as the engine room of the system and the other as office for the work group.

Figure 6. Air-water heat pump.

In Figure 7 we have a detail of the radiant floor. The system comprises a plate of expanded polystyrene with low thermal conductivity that insulates the radiant floor from the ground. Over this layer there is another one made of flexible plastic in which a number of spacers are distributed in order to facilitate the pipe installation. The setup is covered by an additional layer of HIPS (High Impact Polystyrene).

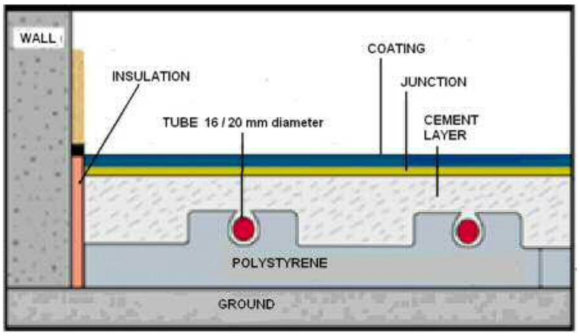

Figure 7. Radiant floor's scheme.

The distribution pipe for the thermal fluid is made of High-Density Polyethylene (HDPE) with an external/internal diameter of 0.020/0.016 m respectively. The whole radiant system is covered by a layer of concrete of 0.05 m thickness and a tile of 0.02 m thickness installed over a thick layer of glue that attach it with the concrete. In order to isolate the foundation, an insulation layer of 0.02 m thickness is located along the perimeter of the foundation. The junction between the insulation perimeter layer and the baseboard is made with an elastic gasket.

EXPERIMENTAL RESULTS

One of the objectives of the research project is to determine the performance parameters for a microphotovoltaic system which feeds a heating and cooling system and works during long periods, [13] and [14]. All the experimental results that are shown in the present paper are according to a pure Pv working mode

The cooling system

The installation finished during the second week of August and after that, the measurement and control system was fitted, being ready for experimental results' evaluation. In figure 5, a simplified diagram is shown. After some adjustments, the first experimental results were obtained during the last week of August and the work lasted until September 24th, when the outdoor temperature dropped and cooling was not needed anymore. The experiment consisted on maintaining laboratory's indoor temperature around 25ºC, as the Spanish regulation indicates, according to [15].

The following exposes some results obtained during August 28th and September 6th: generated electricity; power supplied to the heat pump; cooling production; energetic efficiency and indoor temperature.

August 28th 2012

Figure 8 shows that the photovoltaic field starts the electricity production and storage at 07:22 hours. The Pv production at 9:30 hours reached 0.3kW, which was increasing until a maximum value of 1.7kW at 12:30. Since this moment, the Pv electricity generated decreases until approximately 1kW at 14:45 hours and it keeps at this value until 18:15 when it decreases again, due to the solar sunset at 20:25.

On the other hand, at 7:00 hours batteries' voltage was 24.8 V, which dropped instantaneously to 23.8 V when the electric consumption of the heat pump started. Since that moment, the voltage decreased to 23.3V at 9:20 hours, due to the simultaneous phenomenon of batteries' charge by the Pv field and feeding the heat pump which implies theirs discharge.

In advance, the batteries' voltage increased until reaching their maximum value of 28V at 12:30

hours. This value keeps until 17:25 hours, when the solar radiation dropped below 650 W/m^2, as it is shown on figure 2. After that time, the solar radiation decreased until the sunset and so did it batteries' voltage.

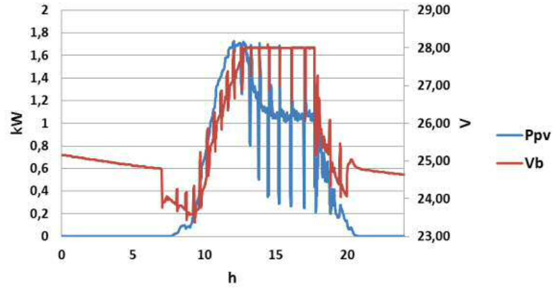

Figure 8. Electric energy produced and voltage.

It is notorious that the Pv electric production decreased from its maximum value of 1.7 kW to 1 kW between 12:30 and 18:15 hours. However, the solar radiation, which at 12:30 hours was 850 W/m^2, increased until a maximum value of 1050 W/m^2 at 14:45 and kept over 850 W/m^2 until 17:00 hours. This efficiency lose would be related to the storage system's limitations. In fact, the MPPT controller protects the batteries of damages, decreasing the Pv production when the batteries are getting charged in absorption mode, according to manufacturer's instructions. This mode of operation is still being tested in order to improve the performance of the batteries during the mid-day hours.

The process of battery discharge continues during night while the system is stopped.

Figure 9 presents the electric power absorbed by the heat pump and the cooling capacity produced. The figure shows how at the start instant the heat pump absorbs 1.2 kW and produces 3.9 kW of cooling power. During the period between 7:00 to 8:00 hours, the power consumption decreases until 0.6 kW and the cooling capacity until 2.4 kW.

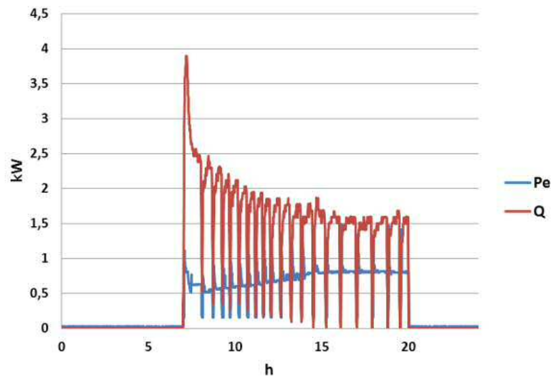

Figure 9. Power input and cooling produced.

The performance of the system during this period depend on the thermal inertia of the floor and the building, that have been exposed to the outside temperature and solar radiation.

The power absorbed between 08:00 and 15:00 hours increases gradually until it reaches a maximum value of 0.8 kW, this value is maintained until 20 hours. During this total period, the cooling power decreases from 2.4 kW to 1.6 kW. The percentage power supplied by the Pv field to heat pump was 100% for all the days.

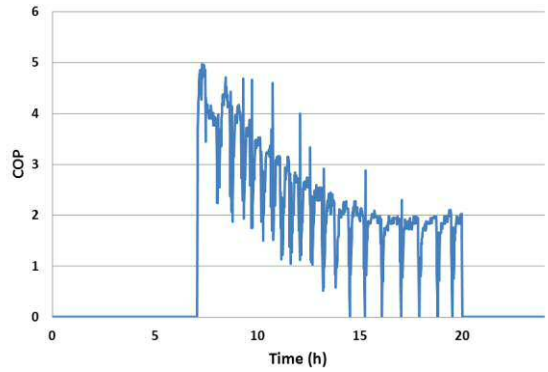

Figure 10. Coefficient of Performance.

The energy efficiency (COP) is presented in Figure 10. At the start instant, when the radiant floor is warm, the heat transfer and efficiency is maximum, obtaining a COP = 5 at 07:20 hours. From this moment, the COP decreases until a value of 2 at 20 hours.

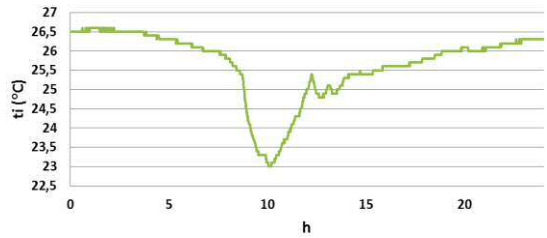

Figure 11. Indoor temperature.

The result of all these processes is shown in figure 11, where the indoor temperature variation is presented. At 07:00 the value of this temperature is 26ºC and decreases to 25.5°C at 08:30 hours, when the research group arrives to the laboratory. Between 08:30 and 10:00 the temperature drops to 23 °C. This is due to the following reasons: on one side, the batteries are supplying electricity to the heat pump producing cold water at 7 °C that flows through the underfloor, cooling the building, and, on the other side, the first operation of the staff when arriving at the workplace is open the windows to ventilate the building, so that the vapours emitted by the batteries and that have been accumulated overnight are expelled outside. As a result of this hygienic operation external air that, as is shown in figure 3, has a temperature of 17.0 ºC at this hour, enters the building helping to cool it down to 23 °C (free cooling).

Once the ventilation operation is finished, when the windows had been closed, the temperature rises up to 25 °C until around 12:00 hours. From this time, the temperature continues to increase, reaching 26 °C at 20:00 hours. Local legislation is, therefore, accomplished [15].

September 6th 2012

Figures from 12 to 15, present a similar behaviour. The results of this day have been included as verification.

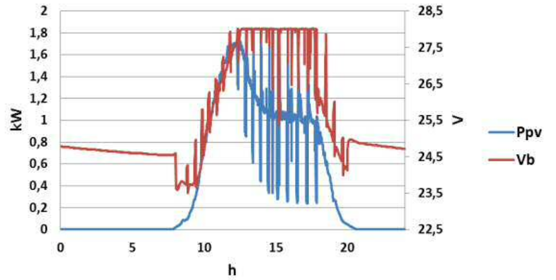

Figure12. Electric energy produced and Voltage.

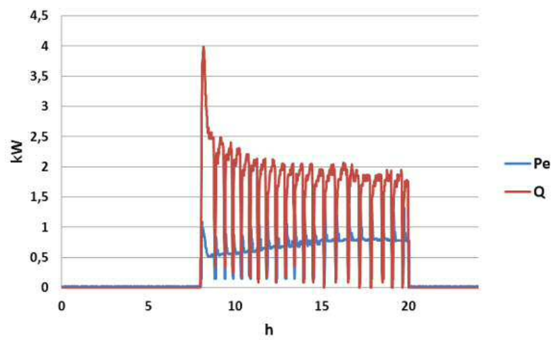

Figure 13. Input electric power and cooling.

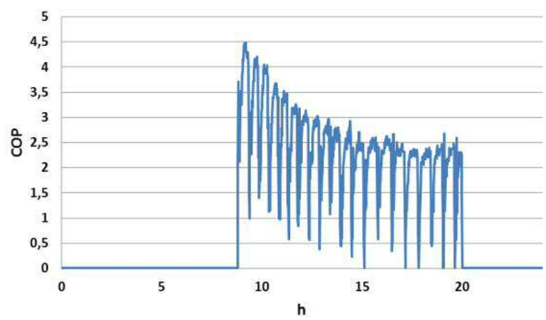

Figure 14. Coefficient of performance.

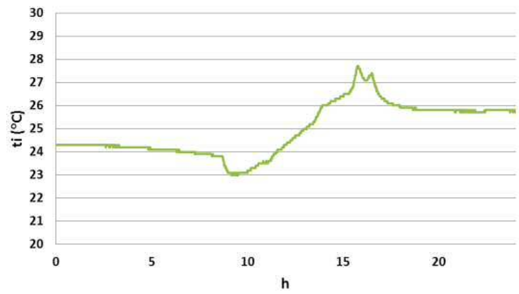

Figure 15. Indoor temperature.

The maximum daily working period was from 8:00 to 20:00 hours.

Period's results (28/08/2012-24/09/2012)

On figures 16 and 17 some results are shown:

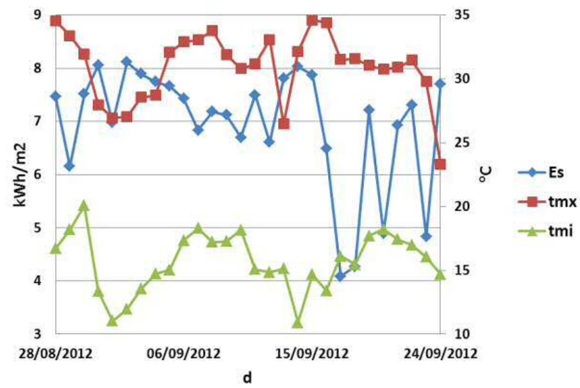

Figure 16. Daily solar energy, maximum and minimum temperature.

Figure 16 shows the solar energy intercepted during this period. We can see that until the middle of September there are days that reach values of 8.0 kWh/m^2, the average value until then is between 7.0 and 7.5 kWh/m^2. From the 15th of September the variability of the values increases. The solar energy intercepted in the total period was 3634 kWh. The maximum outdoor temperature reached was 35 ºC, being the minimum 10 ºC about September 15.

In figure 17, the power absorbed by the heat pump, the cooling production and the COP have been plotted. The electricity supplied to the heat pump was 211 kWh and the cool generated 542 kWh, the COP for the period was 2.6. The overall performance of the solar energy conversion to electricity supplied to the heat pump was 5.8% and the efficiency of solar energy conversion into cold 14.9%. The thermal demand was 560 kWh from where the fraction covered by solar energy was 96.8%.

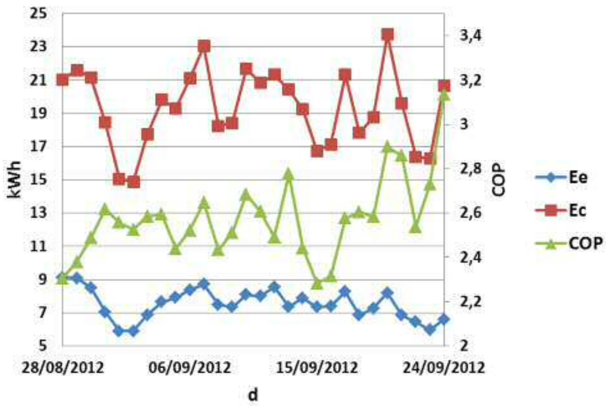

Figure 17. Power cooling, electricity and COP.

The heating System

Figure 18 shows a schematic of the heating system. Its components have been already described in figure 5. Now the function of the heat pump is produce heat for heating the building, in order to keep the indoor temperature within the legal Spanish limits, between 21 and 23 °C [15].

Day 03/12/2012

Experimental results obtained on December 3rd 2012, are presented below, operating exclusively with photovoltaic electricity that had been stored the day before by the batteries and also with the energy generated throughout the day. The facilities start work at 8:30 and end at 16:00 hours.

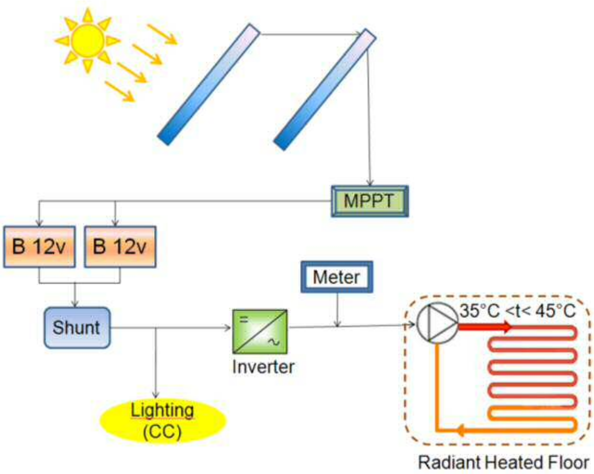

Figure 18. Heating diagram flow.

Figures 19 and 20 contain graphs of the environmental variables that characterize the energy of this day. We see that the minimum outdoor temperature of -2.7 ºC was reached at 7:30 hours while at 16:40 hours the maximum outdoor temperature was 11.0 ºC. In Figure 19 the intercepted solar radiation per unit area is plotted, presenting a sunny day until 15:67 hours with a peak around 1027 W/m^2 at 13:17.

The sun rises at 8:67 hours and sets at 18:00 with a duration of 9.33 hours

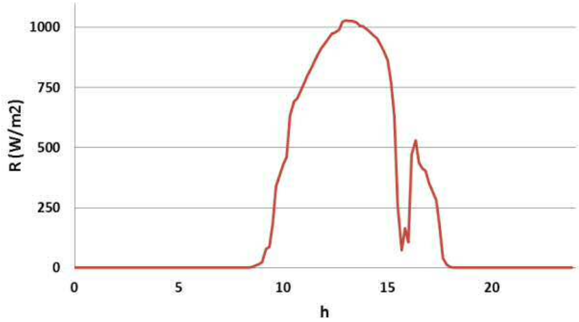

Figure 19. Solar radiation.

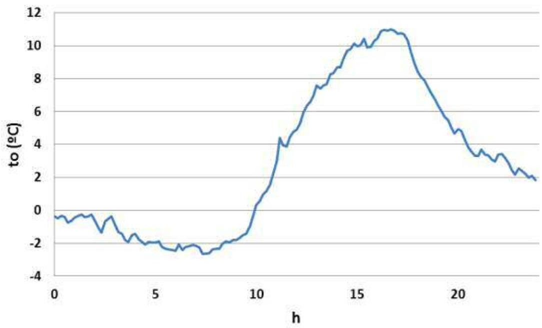

Figure 20. Outdoor temperature.

In Figure 21, it is shown that the photovoltaic field starts the electricity production and storage at 08:20 hours. The Pv production at 9:30 hours reached 0.07 kW, which was increasing until a maximum value of 1.7kW at 11:45. Since this moment, the Pv electricity generated kept around this maximum value until 15:00 hours. Since this moment, it decreased until the sunset at 17:40 hours.

On the other hand, at 08:30 hours batteries' voltage was 25.6 V, which dropped instantaneously to 23.3 V when the electric consumption of the heat pump started. Since that moment, the voltage decreased to 22.3 V at 9:05 hours. From this moment, until 11:00 hours, batteries' voltage increased up to 27 V, due to their charge by the Pv field and the fact that the electric supply to the heat pump was interrupted. At 11:00 hours, the heat pump is feed again, while the batteries' voltage kept around 25 V until 16:00 hours, when the heat pump stopped.

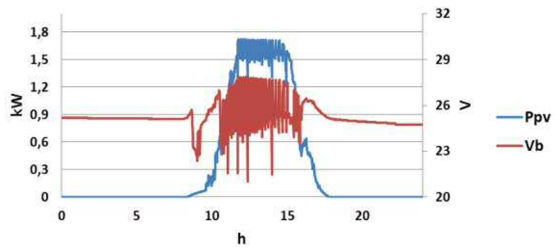

Figure 21. Electric energy produced and voltage.

It can be seen on figure 21, that the Pv electric production kept around 1.6 kW between 11:45 and 15:00 hours, which coincided with the maximum values of solar radiation, according to figure 19. In this working mode, the MPPT controller supplied the maximum power available as the batteries did not get in their absorption mode.

Figure 22 shows the electric power supplied to the heat pump and the heating power supplied to the heating floor. At 8:30 the inverter begins supplying photovoltaic power to the heat pump with an output of around 2 kW. About 9:15 hours, this phase ends with the depletion of the batteries.

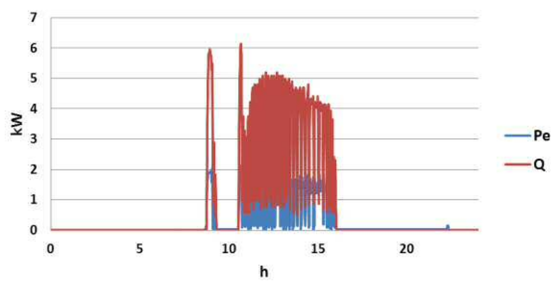

Figure 22. Input electric power and heating.

During this period the heating power generated reaches a maximum value of 6 kW, while the COP reaches a maximum value of 3.8 at 09:16 hours, see figure 23.

From 11:00 hours, when the solar radiation has recharged the batteries, the PV electricity supply to the heat pump starts again and remain until 16:00 hours with an average power of around 1.65 kW that generates an average heating power of 4.5 kW, approximately, with a mid-day peak of 5 kW.

The COP reached a maximum value of 3.8 at 11:00; 13:50 and 15:50 hours. On the other hand, the COP was 1.7 and 1.8 at 12:88 and 15:55 hours. The daily COP average was about 3.0, Figure 23.

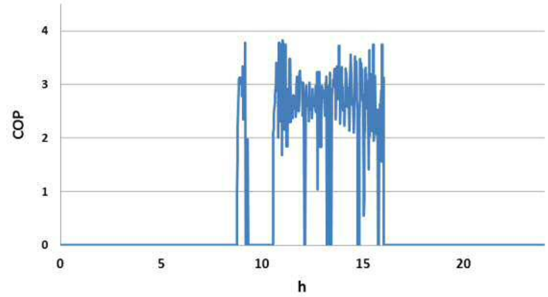

Figure 23. Coefficient of Performance

The intercepted solar energy during the day was 105.4 kWh; the Pv electricity generated was 8.4 kWh; the Pv electricity supplied to heat pump was 6.6 kWh and the heat generated by the heat pump and supplied to the radiant floor 20.0 kWh.

Figure 24 shows the indoor temperature variation, which was 9.8°C at 8:30 hours, reaching 19.5°C at 16 hours and decreasing until 16.5 at 24 hours.

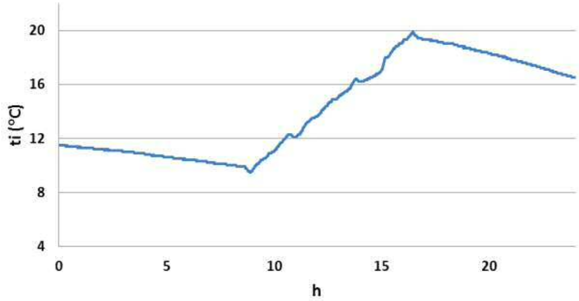

Figure 24. Indoor temperature.

The minimum comfort temperature (18ºC) was obtained at 15:22 hours and was maintained over until 20:83.

CONCLUSIONS

An air conditioning and heating system to regulate the temperatures of a specific building has been designed with a maximum cooling and heating thermal load of 4.0 kW and 6.0 kW, respectively, using a photovoltaic field of 16 Pv modules with total area of 21 m^2 (18.7 m^2 useful area). Each module generates a nominal peak power of 180 watts.

Air conditioning mode

The solar system has worked since 28th August to 24th September, supplying electricity to the reversible air/water heat pump.

Analyzing the performance of the system working in cooling mode in to different sunny days, the following conclusions have been obtained:

28th August results

The average daily solar radiation over the panels was 7.4 kWh/m^2, 118.4 kWh in total. The maximum power output was 1.7 kW and the electrical energy transferred to the heat pump, 9.1 kWh/day. The daily output of the conversion to useful electricity was 7.7% and the cold produced 23.5 kWh/day with a daily overall solar-cold conversion of 19.8%. The efficiency of the heat pump varied between a maximum value COP = 5 and a minimum COP = 2, being the average COP about 3. During this hottest day, when the maximum outdoor temperature was 35 ºC, the indoor temperature remained within legal limits, 25°C approximately.

Air conditioning period

Analyzing the results obtained over the period of study, the following conclusions have been obtained: The total solar energy intercepted was 3634 kWh, producing 211 kWh of electricity supplied to the refrigerator machine that generated 542 kWh of cold. The conversion efficiency to electricity was 5.8% and the final solar-cold conversion was 14.9%. The COP of the heat pump was 2.6 and the solar fraction 96.8%.

Heating mode

The solar system has worked since 30th November, supplying electricity to the reversible air/water heat pump. Next we show the conclusions obtained during December 3, day.

The intercepted solar energy during the day was 105.4 kWh; the Pv electricity generated was 8.4 kWh; the daily efficiency of the solar energy to Pv electricity conversion was 8%, depleting until 6% when the supply to heat pump is considered. The global efficiency solar radiation-heating was 20%, approximately. The maximum comfort temperature reached was 20ºC at 16:15 hours.

NOMENCLATURE

A: area (m^2).

B: battery.

COP: coefficient of performance.

d: days.

E: energy (kWh).

h: hours.

MPPT: Maximum Power Point Track.

P: Power (kW)

Pv: Photovoltaic.

Q: thermal power (W).

R: solar radiation (W/m^2).

t: temperature (ºC)

U: global heat transfer coefficient (W/m^{2}ºC).

V: voltage difference (V).

Subscripts

b: batteries.

c: cool.

e: electricity.

g: generated.

i: indoor

l: load.

in: input.

mx: maximum.

mi: minimum.

pv: photovoltaic.

s: solar.

ACKNOWLEDGEMENTS

The authors want to express their gratitude to the Ministerio de Economía y Competitividad of Spain for funding the research project ENE2010-20650-CO2-01. Also to Ana Rodríguez for your help.

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