PERFORMANCE ASSESSMENT OF A SOLAR-ASSISTED, GROUND-COUPLED ABSORPTION HEAT PUMP UNDER DIFFERENT SCENARIOS IN SUMMER AND WINTER OPERATION

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Abstract

This work describes a novel HVAC system consisting in a solar-assisted ground-coupled absorption heat pump. The aim of this work is to analyze, using a TRNSYS simulation program, the influence of different design parameters, such as the area of the solar collectors; the building occupancy and the using schedule, as well as an assessment of the influence of the weather conditions in the energy performance of the installation during winter and summer season. Finally, an annual analysis of the energy transferred by the main elements of the installation (solar collectors, boiler, geothermal heat exchange, generator, condenser, evaporator, radiant floor) under the actual operating conditions was carried out.

Keywords: Solar energy, solar cooling, sustainable HVAC, geothermal heat exchange, absorption heat pump, radiant floor, TRNSYS

1. Introduction

The building sector consumes almost 120 EJ per year worldwide, representing 30% of total final energy consumption in all sectors of the economy and half of the world's electricity demand. Despite the great efforts of politicians to improve the energy efficiency of buildings, energy use in this sector has increased by almost 20% since 2000. Fossil fuels (coal, oil and natural gas) used directly inside buildings and in the generation of electricity represent a significant part of the energy used. The building sector represent almost 30% of global CO_2 emissions and 36% of the final energy consumed in buildings is used for heating (IEA 2015).

The European Union has identified the building sector as a key sector to achieve the 20/20/20 objective (Reduce greenhouse gas emissions by 20%, achieve that renewable energies cover 20% of final energy consumption and achieve 20% savings in energy demand by 2020), as well as to achieve a reduction of greenhouse gas emissions from 80% to 95% by 2050. To achieve these goals, heating and cooling technologies that use renewable energy as an energy source will play a vital role within a sustainable energy system. This has been identified by the European Commission as a "no-return" point in its energy roadmap towards 2050, as it can provide a "local production" of energy. Renewable energies, in addition to being a decentralized system and a highly available energy sources, has also a significant economic impact: about half of the investment will go to the bottom of the value chain, job creation and economic growth at the local level (Ivanic et al. 2014).

As explained above, there is an interest in integrating different renewable technologies to cover the heating and cooling needs in the building sector, and thus help to reduce the demand of fossil source in this sector. Thus, this work is focused on the energy assessment of an installation, which integrates solar energy and geothermal energy with an absorption heat pump, as a way to cover the heating and cooling demand in an office building. In this paper has done several simulation and the idea is to identify the influences of different parameters such as area solar collector, occupancy of the building and weather conditions (different localization) in the performance of the installation.

2. Installation description

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The facility under study is located in one of the buildings of the CARTIF technology center in Boecillo Technology Park, Valladolid (41º north latitude and 720 m altitude), Spain. It is a building of tertiary use with an approximate area of 1200 m^2.

The main elements of the experimental installation are: The single-effect, lithium bromide - water (BrLi / H_20) absorption heat pump, THERMAX LT 1; a solar field composed by 42 vacuum tube solar collectors, Vitosol 300; a geothermal energy exchanger consisting in 12 vertical boreholes; and an energy storage system based on water tanks. The system was described in detail by (Macia et al. 2013). The characteristics of the main elements of the system are listed in Table 1.

Tab. 1: Main characteristics of experimental installation

Element	Characteristics
Absorption chiller (Thermax LT1)	35 kW
COP nominal	0.7
Vacuum tube solar collectors (Vitosol 300)	84 m^2
Borehole heat exchanger	12 boreholes
Depth of borehole	100 m
Energy storage system (water)	8 m^3
Radiant floor	1200 m^2

The main novelty of the installation is that the absorption heat pump is connected simultaneously to a geothermal field and to a solar collector field, which allows its use throughout the year with two modes of operation (summer and winter):

Summer: The heat pump condenses with the geothermal exchange; evaporator is connected to the cooling radiant floor system that is distributed throughout the building and the generator is connected to both the solar storage tanks and the gas boiler.

Winter: The evaporator of heat pump is connected to the geothermal exchange, condenser is connected to heating radiant floor which supports the conventional systems installed in the building and the generator is connected to the solar tanks or to the boiler, when there is not enough temperature in the tanks. Figure 1 shows the scheme of the installation.

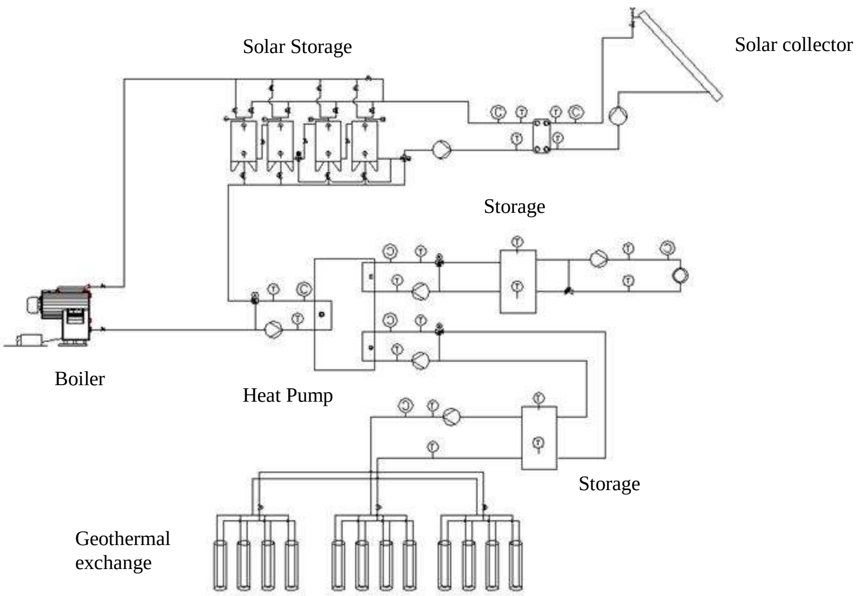


Fig. 1: Schema of experimental installation

3. Simulation approach

In this paper an analysis of the operation of the installation is done under different scenarios, both in summer and winter season. The scenarios that will be analyzed are: influence of solar collector's area; building occupancy, schedule and influence of the weather conditions in the performance of the installation. Finally, an annual analysis of the energy transferred by the main elements of the installation under the actual operating conditions is carried out.

In Figure 2 is possible to observe a schematic of the model developed in TRNSYS for the simulation of the installation, and how the components of the installation are interrelated, from the weather conditions to the building. The simulation model was validated with experimental data collected in actual working conditions of the experimental installation in summer and winter operation modes.

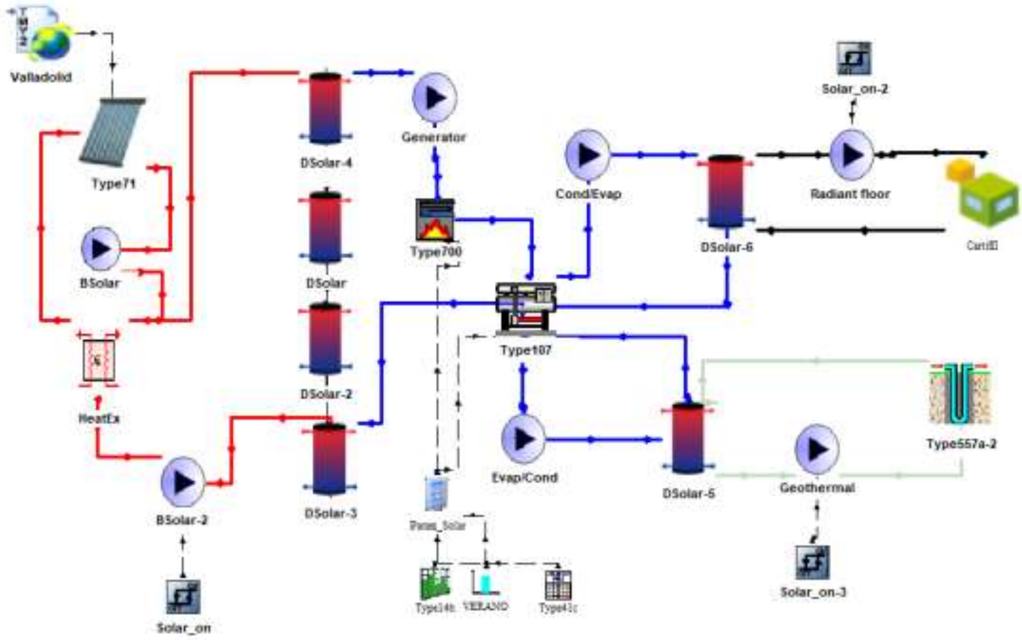


Fig. 2: Diagram of TRNSYS model of experimental installation

The TRNSYS Model is a transient system simulation program with a modular structure that was designed to solve complex energy systems problems by breaking the problem down into a series of smaller components known as Types (Klein 2004). Figure 2 depicts the TRNSYS model scheme developed to simulate the experimental plant. The main modules are described below.

To simulate the performance of the Thermax LT1 absorption chiller, type 107 was used. Since this type uses a catalogue data look up approach to predict the output of the absorption chillers, and the default data file of the type differs from real operation of the installation, several data files of absorption chillers were created, according to the manufacturer technical data.

Type 71 was used to simulate the solar collectors of the solar field. Since standard efficiency curves are calculated for a single solar collector in clear days, at normal sun incidence and nominal flow rate of the water, a few correction factors are introduced in the model, in order to account for series connection, clouds, etc.; details regarding the correction algorithms are given in the TRNSYS documentation. In addition, since evacuated-tube collectors are optically asymmetric, the model takes into account some biaxial Incidence Angle Modifiers (IAM) coefficients for both beam and diffuse radiation. These adjusting parameters are available for any collector tested (ASHRAE 2003) or European Standards (EN12975 – 2:2006)

The natural gas fired boiler used as auxiliary heater is represented by Type 700 in TRNSYS library. The boiler is activated only when its upstream water temperature is lower than a fixed set-point. A vertical ground heat exchanger model must analyze the thermal interaction between the duct system and the ground, including the local thermal process around a pipe and the global thermal process through the storage and the surrounding ground. Ground heat exchanger has been modeled using the known as ‘duct ground heat storage model’ (Claesson et al. 1981). This model assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes, and conductive heat transfer to the storage volume. Also U-tube pipe parameters correspond to the properties of polyethylene pipes DN 32 mm PE100.

Type 4 is used to simulate the thermal energy storage water tanks. Simulation is based on the assumption that the tanks can be divided into N fully-mixed equal sub-volumes. The storage tanks are also equipped with a pressure relief valve, in order to account for boiling effects. The model takes into account the energy released by the fluid flowing through the valve, whereas the corresponding loss of mass is neglected. The temperatures of the N nodes are calculated on the basis of unsteady energy and mass balances. For the radiant floor system in the building, TRNSYS type 56 component was used. Building was simulated using TRNBUILD taking into account internal gains by occupancy, working schedule and the radiant floor was simulated as active slab. Weather conditions are represented by the Typical Meteorological Year (TMY) for Valladolid (Spain). Temperatures, wind speeds and solar radiations at regular time intervals are read by a data processor to generate direct and diffuse radiation outputs for a number of surfaces with arbitrary orientation and inclination.

The control strategy that has been developed for the summer and winter operation simulation may be separated in four principal components, each one with its own conditions.

The solar field consists of several elements: solar collectors, primary pump, secondary pump, heat exchanger and storage tanks. The primary pump switches on between 9:00 and 20:00 h every day. The secondary pump has two conditions that it has to carry out before switch on: the first condition is that primary pump is switched on, and the second condition is that the outlet temperature of the solar collectors is higher than the solar storage tanks temperature.

The control for the switch on of the absorption heat pump has to achieve three simultaneous conditions: *Schedule*: The building is occupied between Monday and Friday from 7:00 to 15:00, so the heat pump only operates on these days. *Solar conditions*: In this simulation the installation only operates with solar energy, without the boiler back up. The solar condition is that temperature of storage tank is above the set point generator temperature. *Demand condition*: Summer, heat pump is only in operation when evaporator storage tank temperature is between 8ºC and 15◦C. Winter, heat pump is switch on when condenser storage tank is between 28º and 30ºC.

The control for the switch on of the pump of the geothermal heat exchanger has to fulfill two conditions: that absorption heat pump is in operation and that the temperature of the condenser storage tank is above the condenser set point temperature (summer season) or the temperature of evaporator storage tank is under evaporator set point temperature (winter season).

The control for the switch on of the pump of the radiant floor circuit has to fulfill two conditions: the building occupancy schedule, and the temperature of the evaporator storage tank being between10ºC and 15ºC in summer or condenser storage tank being between 28ºC and 30ºC.

4. Results

On this section, the assessment of three scenarios during winter and summer are analyzed, solar collector area, building occupancy and weather conditions. For the simulation, the summer season is from 1st June to 30th September, and winter season is from 1st October to 31th of May.

Performance of the installation will be evaluated in terms of some indicators described by (Macia, 2016) such us solar fraction defined by equation 1, solar efficiency defined by equation 2, and COP of the heat pump, defined by Equation. (3).

$$Solar\ fraction = \frac{Q_{solaruseful}}{Q_{gen}} \quad \text{(eq. 1)}$$

$$Solar\ efficieny = \frac{Q_{solaruseful}}{Q_{solaresource}} \quad \text{(eq. 2)}$$

$$COP_{summer} = \frac{Q_{evap}}{Q_{gen}}, COP_{winter} = \frac{Q_{cond}}{Q_{gen}} \quad \text{(eq. 3)}$$

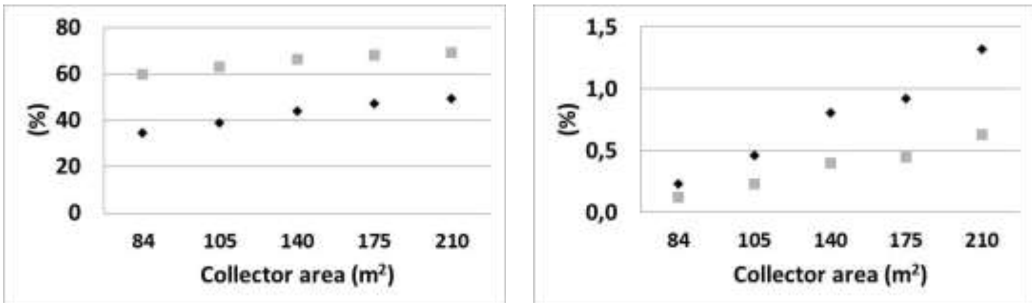
Where Q_{evap}, Q_{gen} and Q_{con} are the energy transferred to the evaporator, generator and condenser of the heat pump, calculated by integrating numerically the respective heat flows. $Q_{solaresource}$ is the total amount of solar energy captured by the solar field during the considered period of time. $Q_{solaruseful}$ is the useful energy used for the installation. Qevap evaluated through equation (4).

$$Qevap = \sum \dot{m}_p \, C_p \left(T_{eva,i} - T_{eva,o}\right) \Delta t \quad \text{(eq. 4)}$$

Where $\dot{m}_p$ is the flow through the evaporator. C_p is the fluid specific heat capacity. $T_{eva,i}$ is the inlet temperature to evaporator. $T_{eva,o}$ is the outlet temperature to evaporator and Δt is the time interval.

4.1 Performance of the installation for different solar collector area

One of the difficulties when designing these types of installations is to know the best relation between the area of solar collectors and the power of the heat pump. For this reason, it has been decided to make seasonal simulations (summer and winter) of the installation for several areas of solar collector. Figure 3 shows the relation between the solar fraction (%), solar efficiency and solar collector area for summer (a) and winter (b).



a. Summer, solar fraction (◆) solar efficiency (■) **b. Winter, solar fraction (◆) solar efficiency (■)**

Fig. 3: Relation between solar fraction and solar collector area for summer and winter

In summer, when the solar collector area increases from 84 m^2 to 210 m^2, the solar fraction increases from 34% to 50%, which means that 50% of the energy demand of the heat pump is covered by solar energy. In figure 3a, it can be seen, that by increasing the area from 175 m^2 to 210 m^2, the solar fraction does not change, and it is in accordance with (Eicker et al. 2014), who say that the solar fraction increases until achieve the saturation. This demonstrates that in order to avoid overcosts in this kind of installations, the design must be done with caution, and always trying to undersize in order to achieve higher hours of operation with a lower investment. In figure 3b is clear that, although the solar collector area increase from 84 m^2 to 210 m^2, the solar fraction just rises from 0.2% to 1.4% and with solar efficiency less than 1%.

These results show that it is possible to use this installation in both summer and winter seasons. The using of absorption heat pump in winter with other auxiliary energy source is feasible, because it will have higher performance than using the energy of the boiler in a direct way for the heating of the building by the radiant floor. In addition, the primary energy consumption is reduced when it is compared to conventional installations.

4.2 Performance of the installation as function of building occupancy

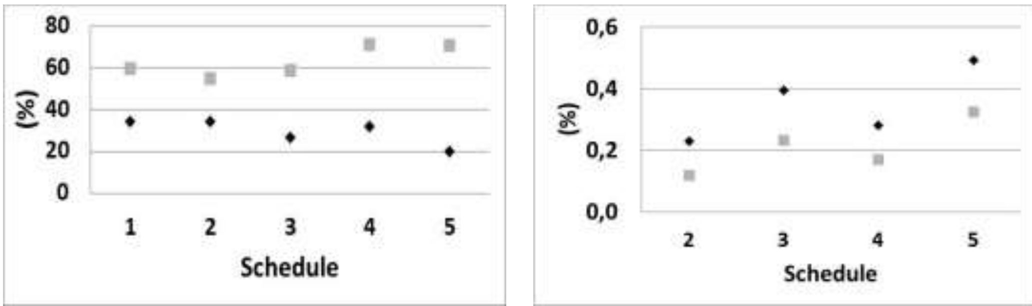
A simulation has been carried out to know if there is any influence of the building occupation schedule on the solar efficiency and solar fraction of the installation. . The schedules were chosen to cover the most common work schedules in Spain, which according to (Nogareda et al. 2014) are: morning and afternoon 40.2%, morning 28.7%, 24 hours 7.2% , morning or afternoon 14.5%, just nights 1.7%, just afternoon 4.6% and 3.1%

corresponding to other work schedules. The five schedules of occupation defined for the simulations are listed in table 2.

Tab. 2: Schedule of building occupancy, absorption heat pump and radiant/cooling floor whole year

Schedule	Days of working	Schedule of building	Schedule of heat pump	Schedule of radiant/cooling floor
1	Monday to Friday	07:00 – 15:00	07:00 – 15:00	09:00 – 15:00
2	Monday to Friday	07:00 – 15:00	04:30 – 11:30	04:30 – 12:00
3	Monday to Friday	07:00 – 15:00	20:00 – 6:00	20:00 – 06:00
4	Monday to Friday	06:00 – 20:00	06:00 – 20:00	06:00 – 20:00
5	Monday to Friday	24 hours	24 hours	24 hours

The figure 4 shows the result of the simulation for both season summer and winter. The assessment was done with two indicators: solar fraction, solar efficiency.



a. **Summer simulation** b. **Winter simulation**

Fig. 4: Solar fraction (◆) and solar efficiency (■) of installation as function of schedules.

In summer, when comparing the 24 hour operating hours (schedule 5) and the CARTIF schedule (schedule 1), the efficiency of the installation is higher in the 24 hour schedule with 70% compared to CARTIF with 60%. This result shows that is better from the solar energy use point of view keep the building open 24 hours. On the other hand, the solar fraction changes from 35% in the CARTIF schedule to only 20% solar fraction in the 24 hour schedule. This decrease in the solar fraction is due to the increase in the energy demand of the generator to cover the 24 hours of operation, causing that the solar installation does not have the sufficient capacity and it is necessary a greater support of the auxiliary energy, CARTIF schedule to 24 hours schedule the generator demand increases 2.6 times.

In winter, with 84 m^2 of solar installation, the solar fraction for any of the simulated schedules is less than 0.5%, demonstrating the need for an auxiliary energy source to cover demand.

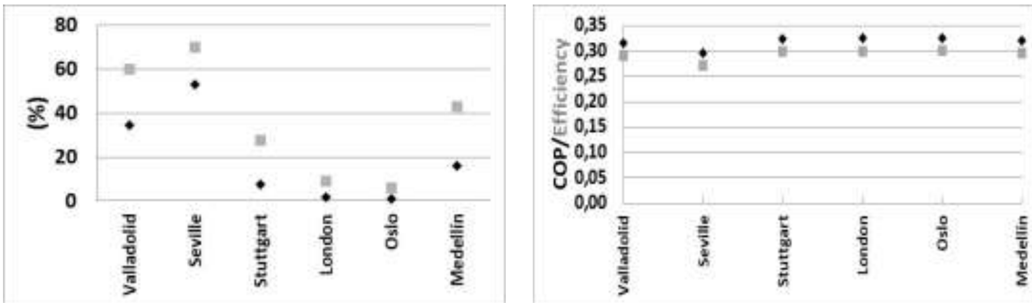
4.3 Performance under different weather conditions.

To make an analysis of the influence of climatic conditions on the performance of the installation, simulations for different weather conditions were carried out. For the selection of cities to be simulated, the climatic severity index has been taken into account, according to the Technical Building Code (CTE, 2006) the climatic severity of a locality is the quotient between the energy demand of any building in that locality and the energy demand of same building in a reference locality. The advantage of making the geographic classification based on the index of climatic severity, (Rodríguez, 2015) is that in contrast to the degrees day total year; this index takes into account other variables as the radiation.

According to (Rodríguez, 2015) with the use of the climatic severity index it is possible to discriminate between cold areas of Europe with high solar radiation in winter and other areas with low solar radiation in summer, that having classification by degrees days would not be possible differentiate.

According to the classification explained before, it has been decided to do the simulation for six different cities, each one belonging to a different zone. They are: Valladolid, Seville, Stuttgart, London and Oslo and Medellin.

For the simulations in different climatic conditions, the same characteristics of the heat pump, the building and the same characteristics of the soil have been considered for all the locations. Only the slop of the solar field has been modified according to the latitude of each of the cities. The analysis only has been focused on the influence of both solar radiation and climatic conditions, on the performance of the installation and the heat pump, as well as the solar fraction. The results of simulations are depicted in figure 5.



a. Solar fraction (◆) solar efficiency(■) **b. COP(◆), installation efficiency (■)**

Fig. 5: Solar fraction, solar efficiency, COP of installation as function of weather conditions

Solar efficiency in Valladolid and Seville is greater than 60%, which means that more than 60% of the energy of solar field becomes useful energy for the installation. In Oslo and London the efficiency is less than 9% showing that useful solar energy is negligible and it would be necessary to increase the collector area to increase the solar fraction. The results of simulation during winter season for the main elements of installation are presented in table 3.

Tab. 3: Energy of main elements of installation during winter season

City	Q_{boiler} (kWh)	$Q_{solaresource}$ (kWh)	Q_{useful} (kWh)	Q_{gen} (kWh)	Q_{con} (kWh)	Q_{eva} (kWh)	Q_{floor} (kWh)	Q_{geo} (kWh)
Valladolid	8666	16974	20	8686	11486	1800	10425	1968
Seville	6701	21751	372,9	7122	9389	1509	6673	1203
Stuttgart	9545	11047	0	9768	12965	2010	9456	2463
London	9217	9545	0	9278	12270	1913	9456	2184
Oslo	11196	8198	0	11118	14808	2272	11892	3197

The amount of solar energy used by the heat pump during winter (solar useful energy) for three cities Stuttgart, London and Oslo is zero and all energy demand must be covered by the boiler. On the other hand, for Valladolid the contribution did not reach even 1% of total energy demand. A greater contribution was achieved in Seville, with 5% of the total demand of the generator. These results indicated that for the demand conditions of the heat pump with 84 m^2 of solar collector, the solar fraction is zero or very low.

When comparing the solar energy (Qsolar) in Table 3 among the different cities, it is seen that in Seville is where there is a greater uptake with 21750 kWh, but of this energy the contribution to the installation is only 372 kWh, which represents a total of 21378 kWh of solar energy were not used. Oslo on the other hand, it was the city with a lower solar energy with 8198 kWh, this is due to the few hours of solar radiation in winter. This result suggests that in winter the solar energy should be given another use, such as the preheating of the supply water to the boiler.

In table 3, it can also be seen that the demand for radiant floor is higher in Oslo (11892 kWh) being almost double the demand of Seville (6673 kWh), it is expected since the weather conditions in Oslo are more severe than in Seville. The coefficient of operation of the heat pump (COP) in all cities was 1.32 and there is no influence of external conditions on the performance of the pump, one of the reasons is that its three exchanges (generator, condenser and evaporator) are not affected by the external conditions, since the conditions of the ground, the conditions of the radiant floor and the conditions of the boiler have been considered equal in all the locations.

4.4 Annual energy balance

Finally, after all the simulations carried out in previous section such as: the influence of the building's schedule, the area of solar collector and the study of the influence of the weather conditions on the performance of the installation. On this section, an analysis of the energy flows by each one of main element of the installation during one year of operation under CARTIF conditions (schedule, location) was done.

Figure 6 display the energies exchanged in each one of the main elements of the installation both in summer and winter season.

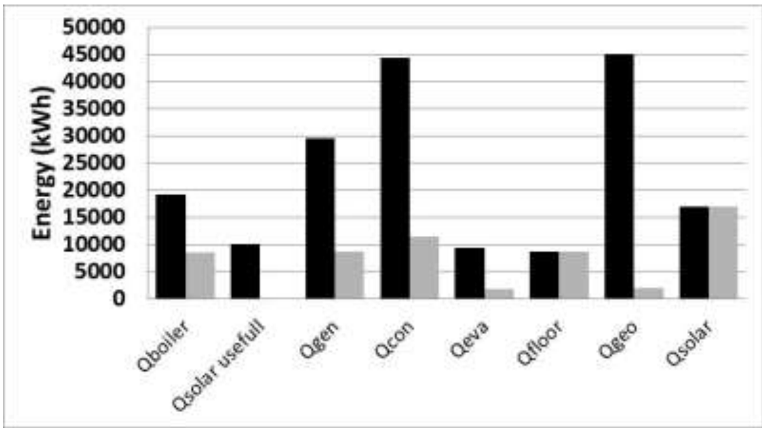


Figure 6. Energy season by each element of installation, summer (■) winter (■)

A holistic analysis of Figure 6 shows that there is a greater exploitation of the facility in summer than in winter, since the energies transferred in all elements are greater in summer. The solar useful energy during the winter is almost null even though the solar energy (Qsolar) is even greater than the energy transferred by the boiler, this result suggests to search another use to the solar energy captured, although it is not possible to use it directly in the installation for the temperature conditions necessary for its use, if it is possible to use all "free" energy as preheater of the supply water entering the boiler or for the floor heating in a direct way.

Another result of Figure 6 that should be paid attention, is the energy exchanged with the geothermal field (Qgeo). In the summer, the facility exchange 23 times more energy to the terrain than it absorbs in winter (45008 kWh versus 1968 kWh). This result suggests a more detailed analysis of the geothermal field and its performance over the years in order to avoid saturation of the soil, due to the decoupling between the energy transferred in summer and winter, coefficient of heat transfer is reduced.

5. Conclusions.

In winter, increasing the solar collecting area in Valladolid does not have a significant effect on the solar fraction, the energy captured goes from 17 MWh to 18 MWh, which can be an energy to be used for preheating the supply water to the boiler or to domestic hot water (DHW) of the building. On the contrary, in summer, if the solar collector area increases from $84 m^2$ to $210\ m^2$, the solar fraction increases from 34% to 50%, but above $175\ m^2$ the solar fraction is practically constant. This demonstrates that to avoid over costs of this type of installations, the design must be done with great care and always trying to undersize to achieve higher hours of operation with a lower investment.

The simulations allow concluding that the occupation schedule of the building has an influence on the solar fraction and yield, showing that with more hours of occupation, a higher efficiency is obtained, but the solar fraction decreases.

The analysis of the weather conditions shows that the use of solar energy in winter for this type of facilities, with demand of high temperatures is negligible in all simulated cities, this result suggest that in winter it should be look for other uses for the solar energy in order to increase the useful energy during this season. In summer, on the other hand, in cities such as Seville, solar fractions are achieved in excess of 50% and solar efficiency in excess of 60%. In northern cities, both summer and winter, solar yields remain low; giving to think that perhaps this type of facilities have a better exploitation in countries of the Mediterranean.

96% of the total annual energy transferred to the geothermal field corresponds to its operation during the summer, when the heat pump capacitor exchanges with it. This result suggests a more detailed analysis of the geothermal field and its performance over the years to avoid a saturation of the terrain, generating a degradation of the terrain due to the lag between summer and winter

6. Acknowledgements

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