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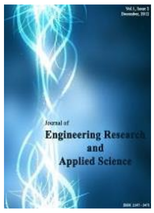

Theoretical performance of solar heat pump residential heating applications

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Abstract
Solar energy systems and heat pumps are two promising means of reducing the consumption of fossil energy sources and potentially, the cost of delivered energy for refrigeration and air conditioning purposes. In order to accomplished for this purpose, thermal energy storage (TES) systems are becoming an interesting option. TES is a key component of any successful thermal system and a good TES should allow minimum thermal energy losses. The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy. In this study, the performance of solar heat pumps with latent heat energy storage for residential heating applications was investigated theoretically.

Keywords: phase change materials (PCMs), Solar heat pumps; residential heating

1. Introduction

Heat pumps have a tremendous potential to bring renewable heating into houses. Because heat pumps are electricity-driven, there is a direct interaction with other energy demands within the built environment, such as PV panels and electric vehicles. By using heat pumps in a flexible way (i.e. a 'smart grid'), it is possible to better integrate these different electricity-producing and electricity-consuming devices. This helps the energy supply to be more reliable, with a higher share of renewable input. Heat pumps in smart grids can contribute to a better energy supply in many ways, and the basic driver for the work within Annex 42 has been to enhance the realization of the different solutions [1, 2, 3].

Solar energy systems and heat pumps are two promising means of reducing the consumption of fossil energy sources and, potentially, the cost of delivered energy for domestic space heating and cooling with water heating [1-4]. A logical extension of each is to try to combine the two to further reduce the cost of delivered energy. It is widely believed that solar heat pump combined systems will save energy, but what is not often known is the magnitude of the possible energy savings and the value of such savings relative to the additional expense [5-8]. So, renewed interest is being directed at solar heat pumps by scientists, architects, engineers, manufacturers, and building owners as well as in the marketplace in general. The principal advantage of employing solar radiation as a heat pump heat source is that, when available, it provides heat at a higher temperature level than do other sources, resulting in an increase in the coefficient of performance (COP). Compared with a solar heating system without a heat pump, the collector efficiency and capacity are materially increased due to the lower collector temperature required [9-17].

The combination of a heat pump and solar energy system would appear to alleviate many of the disadvantages that each has when operating separately. During winter, the energy that could be collected by the solar system, but that would be too low in temperature to be useful for direct heating, may be used as a source for the heat pump. Because the solar collector storage system can supply energy at temperatures higher than the ambient outdoor air, the capacity and COP of the heat pump would increase over those for the heat pump alone, the peak auxiliary load requirement would be reduced, and the combined heating system would seem to operate more economically [7-10]. The operation of the solar system at temperatures near or below room temperature would decrease the collector losses and allow more energy to be collected. The lower collection temperature might allow the use of collectors with one or no covers, and this would reduce the first cost from a conventional two-cover solar system. Finally, for those areas where warm temperatures occur during cloudy periods, the combined system might compensate for the reduced

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performance of the conventional solar system under cloudy conditions and the low capacity of the heat pump in cold weather [1-17].

2. Solar heat pump system

Research and development in the solar-assisted heat pump (SAHP) field has been concerned with two basic types of systems: direct and indirect. In direct systems, refrigerant evaporator tubes are embodied in a solar collector, usually of the flat plate type. Research has shown that when the collector has no glass cover plates, the same collector surface can also function to extract heat from the outdoor air. The same surface may then be employed as a condenser, using outdoor air as a heat sink for cooling [1, 2, 3, 4].

An indirect system employs another fluid, either water or air, which is circulated through the solar collector. When air is used, an air-to-air heat pump may be employed, with the collector being added in such a way that (1) the collector can serve as an outdoor air preheater, (2) the outdoor air loop can be closed so that all source heat is derived from the sun, or (3) the collector may be disconnected and the outdoor air used as the source or sink. When water is circulated through the collector, the heat pump circuit may be of either the water-to-air or water-to-water type. Heat pumps complement solar collectors and heat storage in SAHP systems in several ways:

- Heat pumps are more efficient and can provide more heat for a given heat pump size if their evaporators can operate from a warm source. Thermal energy storage, heated by solar collectors, can provide that warming.
- Solar collectors operate more efficiently if they collect heat at lower temperatures. If the collected heat can be stored at a lower temperature because it is used to warm the evaporator of a heat pump, the collector is more efficient and, therefore, fewer collectors are needed to collect a required amount of heat.
- Heat pumps are the most efficient way in which to use electricity for backup heat for a solar heating system, even if there is no direct thermal connection of the heat pump with the solar collector and storage system.
- Heat pumps can allow sensible and latent heat storage units (e.g., water, PCMs) to operate over wide temperature ranges because stored heat down to 5°C can be used in conjunction with heat pumps to heat a building.

In general, SAHPs can work in three forms: parallel, series, and dual-source systems. A parallel system would use solar energy in the heat exchanger first and then use the air-to-air heat pump when the solar coil is unable to provide the necessary heat. A series system would use the solar energy in the heat exchanger first and then use the water-to-air heat pump when the solar coil is unable to provide the necessary heat. Dual-source heat pumps are currently in the development stage. A dual-source system would have the choice of either an air-heated coil when warm air is available or a water-heated coil when warm water is available. This type of capability would be advantageous in the SAHP, and in applications where well water is available as a source during the heating season. It would also alleviate the need for a cooling tower when the heat pump operates in the cooling mode.

It is not unusual for the SAHP to save up to 20% in operating costs during the heating season compared with an air-to-air heat pump. This represents a heating COP of nearly 3.0. It has been reported that parallel systems can save up to 50% of the energy required when compared with electrical resistance heating, series systems can save up to 60% of the energy normally required, and dual-source systems can save up to 70% of the energy normally required.

A wide variety of options exist to provide air conditioning along with solar heating of buildings. The efficacy of coupling these options with a solar heating system depends strongly on which system is to be used and whether one is considering systems that can already be built reliably or ones that promise optimum performance in the future following extensive development effort. Several SAHP systems are described to illustrate their relationship with air conditioning: the simple parallel system, series system, dual-source system, and cascade system.

2.1. Parallel System

As shown in Figure 1, the parallel system consists of a solar collector, a water-to-air heat exchanger, an air-sourced heat pump, a water-circulating pump, a storage tank, and other equipment. The parallel SAHP system is combining two main components: the solar system and the parallel heat pump system. In this system, the heat pump uses ambient air as an energy source while the water-to-air heat exchanger uses solar energy as a heat source, and they give their energies to the load one by one. Solar energy is used to meet as much of the heating requirement as possible. Thus, the total available energy of the system is the sum of the extracted energies from two different systems (the solar system and the heat pump).

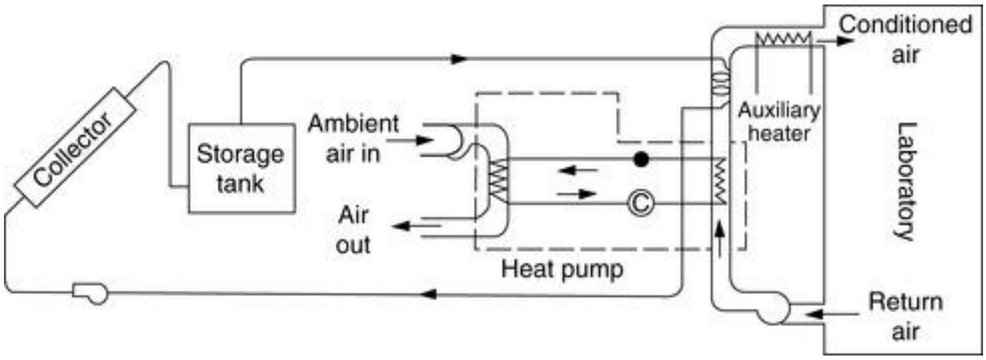

Figure 1. Parallel heat pump system. Reprinted from Kaygusuz et al. (1993).

2.2. Series System

Figure 2 shows a series SAHP system. The solar collector heats water, which is then stored in a tank. The tank provides heat directly to the house if the tank temperature is above 40°C, and the heat pump draws heat from the tank when the tank temperature is between 5 and 40°C. This system has the advantage that the tank can be operated at lower temperatures when required, allowing the collector to operate with high efficiency, and the tank heat storage capacity can be increased by the amount of sensible heat stored between 5 and 40°C. The disadvantage of the system is that when the tank temperature finally drops to 5°C, the heat pump cannot be used further without danger of freeze-up in the water tank. The system shown will not provide air conditioning because there is no way in which to exhaust the waste heat to outside air. It would be possible to provide air conditioning if there were another heat exchanger loop between the storage tank and outside air, but this would add to the cost of the heat exchanger and its associated circulating pump. A development effort is required on the heat pump in this system because residential heat pumps are not currently designed to operate efficiently with evaporator temperatures above 20°C, and this one would have to operate at up to 40°C.

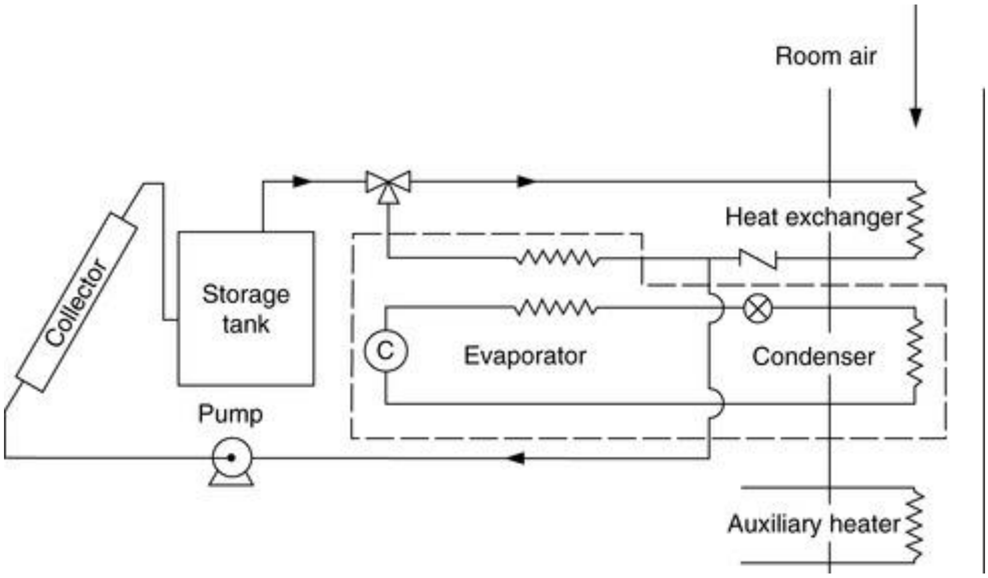

Figure 2. Series heat pump system. Reprinted from Kaygusuz et al. (1993).

2.3. Dual-Source System

The dual-source SAHP system, illustrated in Figure 3, combines the advantages of the parallel and series systems and overcomes their disadvantages. The solar collector, heat storage, and building heat exchanger all continue to work as a simple solar system so long as the tank temperature remains above 40°C. At temperatures below that, the heat pump system is called on by a microprocessor controller, and a decision is made as to whether it is better to draw the heat pump's heat from the tank or from the outside air. The control strategy options are numerous for this system; it can be operated to optimize savings of electricity or to reduce peak loads. It would be the most efficient of all the systems described here. It has the disadvantage that the required heat pump is complex and will be costly to manufacture. Considerable development work will be required to ensure that the unit can be operated in all sequences of its modes with full reliability. With this system, air conditioning is accomplished by operating the unit as a simple air-to-air heat pump in the cooling mode, using only the outside heat exchanger as a condenser. So, it is obvious that the dual-source heat pump system takes advantage of the best features of the series and parallel heat pump systems. The system is not capable of using the storage tank to reduce air-conditioning peak loads during the summer because the heat pump cannot be used to cool the tank to the outside air.

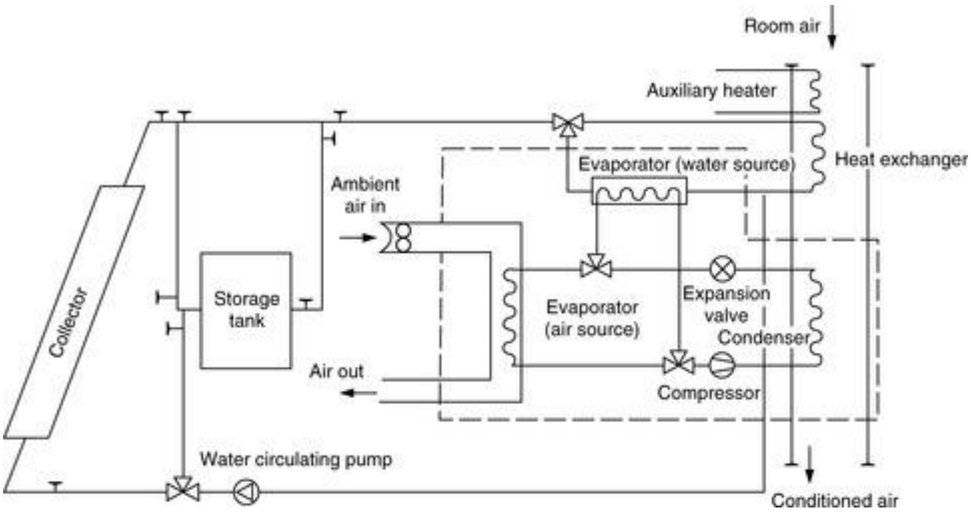

Figure 3. Dual-source system. Reprinted from Kaygusuz et al. (1993).

2.4. Configuration of the phase change energy storage tank

Figure 4 shows the configuration chosen for the storage tank. It consists of a vessel packed in the horizontal direction with cylindrical tubes. The energy storage material ($CaCl_2.6H_2O$) is inside the tubes (the tubes are made of PVC plastic) and the heat transfer fluid (water) flows parallel to them. The storage tank contains cylindrical PVC containers filled with PCM. The void fraction (the ratio between the fluid volume and the storage tank volume) is 0.3. The inside volume and inside surface area of the energy storage tank are, respectively, given by V_{st} and A_{st}. The number of cylindrical PVC containers inside the storage tank is N_c. The radius of the cylinder containers is r_c, and the length of the cylindrical tube containers is given by L. Also, the radius and length of the energy storage tank are given by R_{st} and L_{st} , respectively. The r_c/L is 0.01, and this ratio is small enough to minimize radial heat conduction in the storage material (see Figure 4).

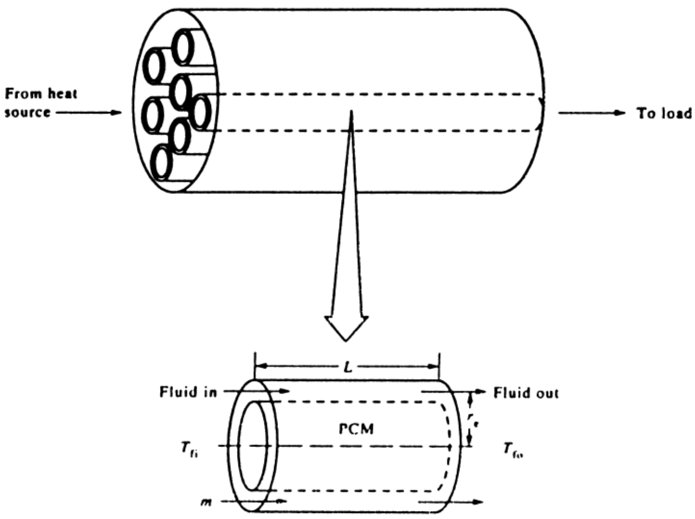

Figure 4. Schematic configuration of the phase change energy storage tank.

2.5. Advantages of solar heat pump (SHP) systems

The success on the market of HVAC technology is determined mainly by the satisfaction of users. In principle, a good energy system should be cheap and easy to operate and should have limited operation costs, a low maintenance effort, and a long lifespan. In the last few decades, users have become more sensitive to environmental problems; however, they are not adequately weighted on the energy costs yet, even if clearly motivated. Most of the time, a customer is more attracted by a system with relatively low investment cost rather than a more environment-friendly solution [1, 2, 4, 8].

International and European norms and standards have redirected the market to environment-friendly systems by imposing an energy labeling to all new HVAC systems and components. This promotes the competition among manufacturers for producing better performing systems at the lowest market cost. Heat pumps and solar thermal collectors are preferential solutions for meeting new restrictive standards on the reduction of CO_2 emissions in new or refurbished residential buildings and, in this sense, SHP systems represent a valuable solution. The large number of ready-to-use SHP systems available on the European market confirms this statement. Kits and turnkey standardized solutions are commercialized in order to reduce the investment costs and the risk of mistakes during installation and to pursue compactness. In order to achieve these results, the standardization of the SHP system layout is fundamental and, thanks to a better design process, this can be reflected in an extended system lifespan (see Figs. 5-13).

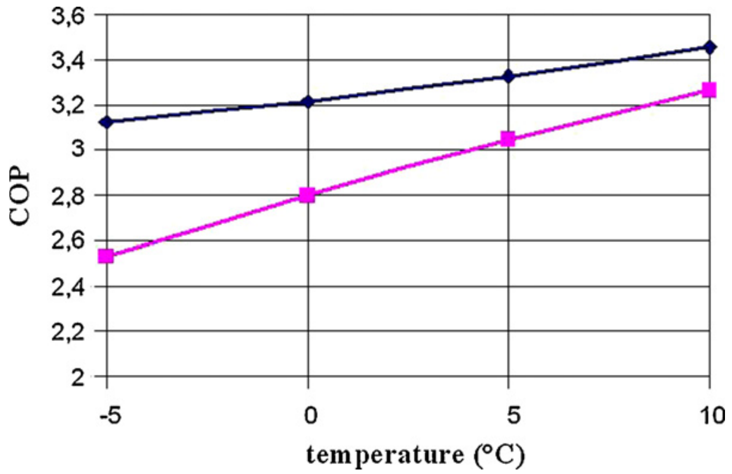

Figure. 5. COP of liquid and air heat pumps as a function of cold source temperature

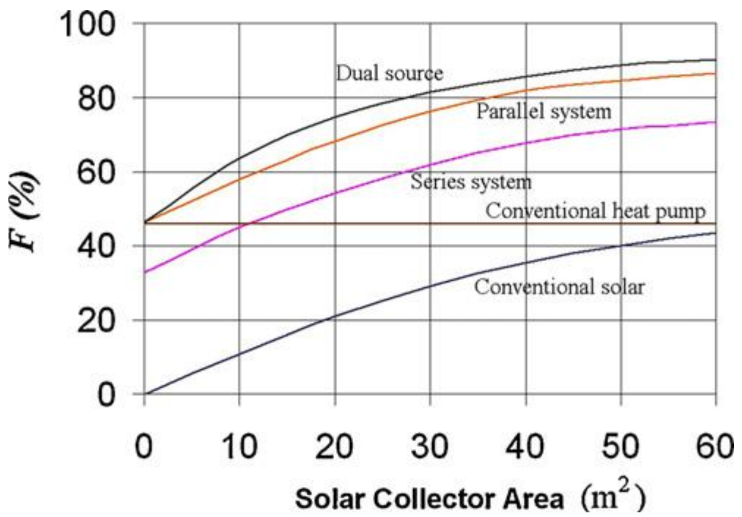

Fig. 6. Fraction of the annual load met by free energy as a function of the solar section area for the systems under consideration.

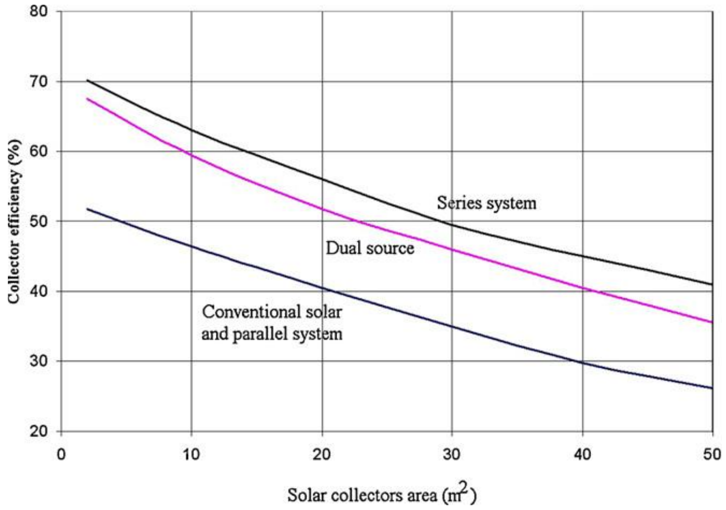

Fig. 7. Solar collector efficiency as a function of collector area for the systems underConsideration

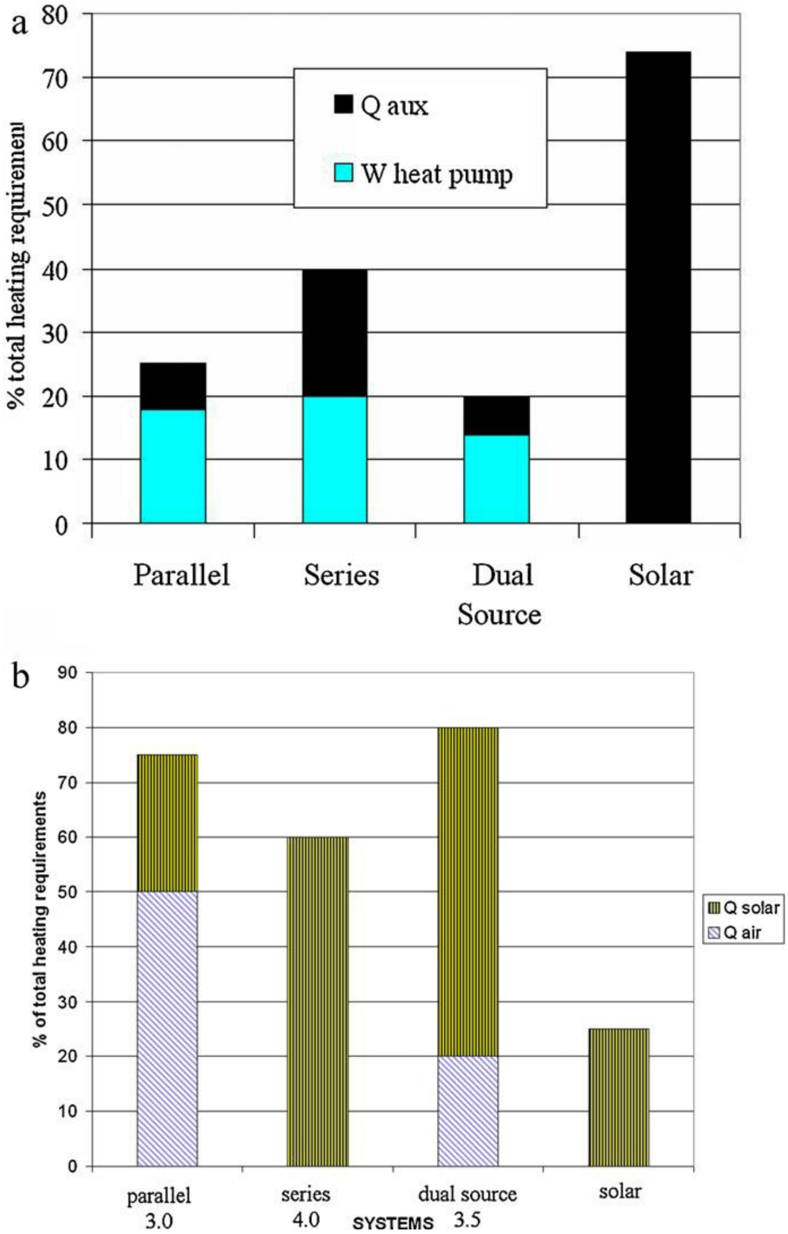

Fig. 8. (a and b) Fraction of the total heating requirement attributable to purchased energy and free energy.

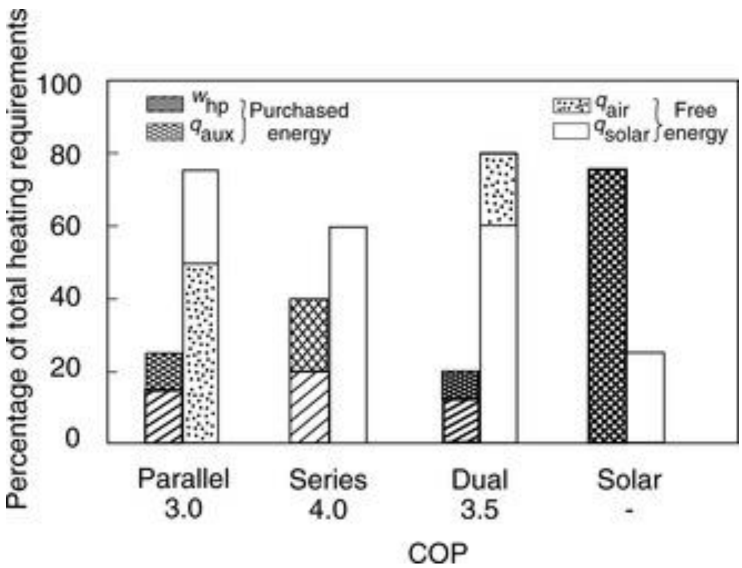

Figure 9. Heating contributions from all possible sources for Trabzon, Turkey

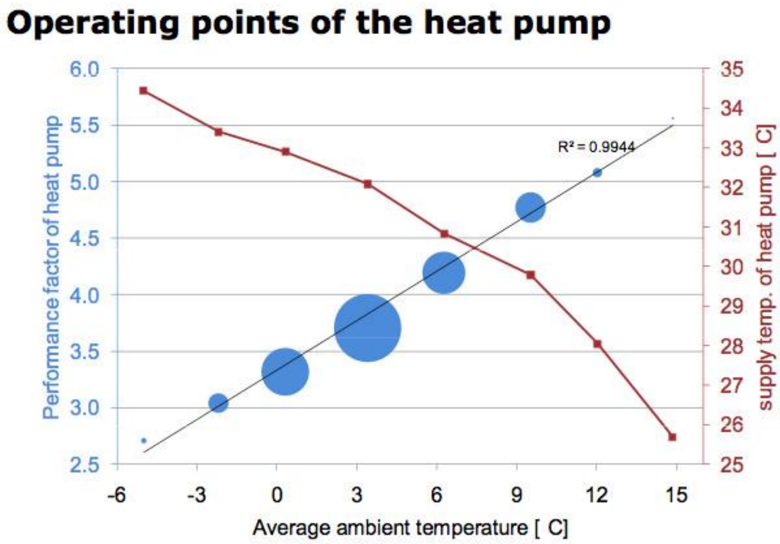

Figure 10. Annual system simulation of air-water heat pump.

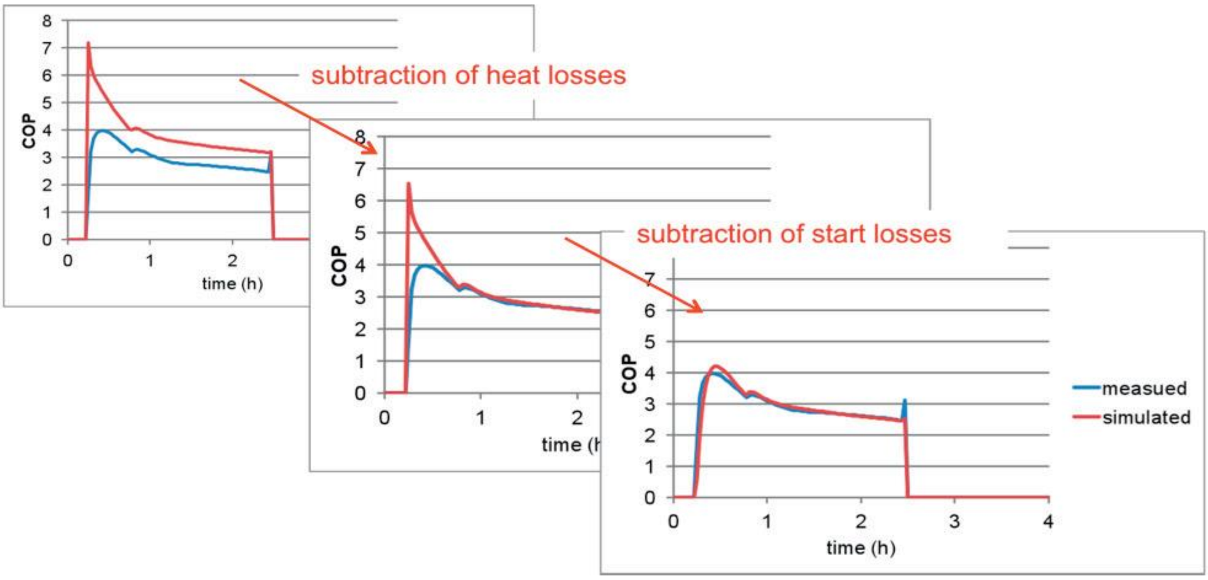

Figure 11. A dynamic model of a heat pump can be improved by taking into account transient heat losses

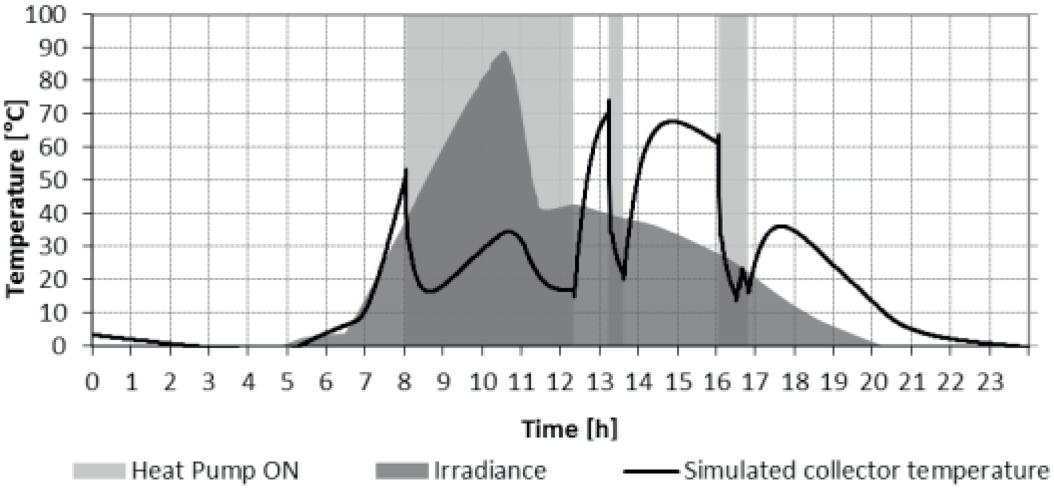

Figure 12. Solar irradiance, simulated collector temperature and HP operating period

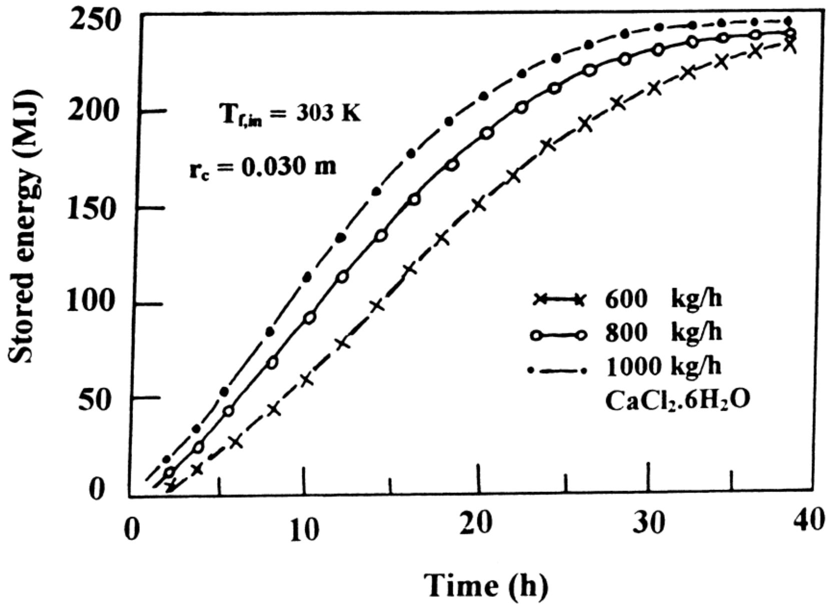

Figure 13. Variation of stored energy with time at different values of Q_{in} and $T_{f,in}$ for $CaCl_2.6H_2O$.

Integrating solar thermal collectors with heat pump systems shows also positive nonenergetic advantages. For example, adopting solar thermal collectors as an additional heat source reduces the yearly operation time of the device resulting in an increased lifespan once again. Moreover, the noise of air source heat pumps is reduced or eliminated in summer, when customers are more likely to open buildings' windows.

Among all these advantages of SHP systems, energetic and environmental aspects have a leading position. The combination of solar thermal and heat pump technologies contributes to increasing the system SPF and consequently in reducing the final energy (FE) consumption of the system and consequently the CO_2 emissions. The additional ΔSPF induced by solar collectors is variable and dependent upon the SHP system configuration (series and parallel), the heat source typology, the surface area of the solar field, and the building loads. A value of ΔSPF per m^2 of solar field has been given according to parallel and series SHP system layouts. The benefit in terms of FE savings is dependent on the SPF_{ref} of a reference system and on the consequent ΔSPF [2].

$$SPF_{ref} = \frac{\int (Q_{SH} + Q_{DHW})\, dt}{\int (\Sigma P_{el})\, dt} \quad (1)$$

$$FE\,(\%) = \frac{FE_{ref} - FE_{SHP}}{FE_{ref}} = \left(\frac{1}{SPF_{ref}} - \frac{1}{SPF_{SHP}}\right) / \left(\frac{1}{SPF_{ref}}\right) \quad (2)$$

According to this equation and assuming a reference SPF_{ref} value of 2.7 for air source heat pump system and an SPF_{SHP} value of 4.5, the final energy savings amount to 40%. Since final and consequent primary energy savings are reflected in an equivalent reduction of the CO_2 emissions by using a conversion factor, the same value of ΔCO_2 can be achieved. In this sense, SHP systems represent a ready-to-use solution for achieving a renewable energy concept in new or existing residential buildings.

3. Conclusions

Solar and heat pump systems is a combined technology that can take a market share in the segment of building heating and cooling since it carries some advantages: high renewable energy share, lower electricity demand, lower primary energy demand, lower CO_2 emission depending on the electricity mix feeding the heat pump. Market share of solar heat pump systems could reach 100 % of new houses in many countries where heat pump technology is well implanted and solar is mandatory for domestic hot water.

When the sun is shining, the collectors will be the primary source of energy for the domestic hot water preparation and for the space heating. Furthermore, the daily solar production can be stored for future use during a few days. When the sun is less abundant or when the solar storage is empty, the heat pump will take over the duty. The source of the primary low-energy "heat" for the heat pump to operate can be air, ground, or water from a river or an aquifer. A nice feature of the hybrid combination is that the solar collectors can also be used as the provider of the primary heat for the heat pump. The two components will then operate in the so-called serial mode.

Combining solar and heat pump technologies is relevant in several aspects: a high renewable fraction can be achieved (solar + the heat pump heat source) and the safety of the solution makes it a good choice for many homeowners. The solar heat can help enhance the performance of the heat pump by raising the evaporation temperature. And the solar heat can be stored at low temperatures (0-80 °C) thus making good use of the collectors even during the cold season, cloudy days or at night. A good use of the latent heat of 1.0 m^3 of water changed into ice around 0° C can also be achieved. Or a good use of the latent heat of 2.0 m^3 of calcium chloride hexahydrate ($CaCl_2.6H_2O$) melted/solidified around 30 ^oC for heating and cooling applications (see Figure 13).

In the long term, solar heat pump could take a significant market share in all solar energy rich countries such as Turkey if electricity is produced CO_2 free and available. Solutions including solar PV could develop and expand for net zero houses and positive energy houses. On the other hand, the components are mature; the combination of solar and heat pump needs however international R&D work to better understand the optimal configurations under several criteria. Solar and heat pump systems can be deployed for both small and large systems. There is no limitation of size in such a combination. Solar and heat pump combination offers many advantages for the developing market, such as:

- It can cover all needs of a building: heating, DHW, cooling, dehumidification;
- Specific combinations can be suited for different applications, climates, etc.
- It offers cooling (active or passive, if ground-coupled);
- It gives a capability of energy storing and supply-demand unbundling;
- Ventilation can also be integrated in compact air units;
- Solar and gas-driven heat pump can be suitable for high-temperature distribution systems as boiler-replacement;
- Part of the locally produced electricity (PV, wind) can be stored on site as thermal energy without stressing the grid.

A supporting policy is needed for:

- Technological development
- Quality assessment of products
- Partnership between R&D teams and HVAC industries
- Sharing of knowledge among countries
- Communication to large audiences and customers
- Clean electricity production that would make S+HP solutions 100 % renewables
- Thermal heat pump development
- Material and system testing platforms

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