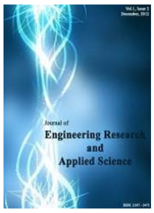
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 11 (2), December 2022, pp 2207-2215
ISSN 2147-3471 © 2022



Modeling of a Residential House Coupled with a Dual Source Heat Pump Using TRNSYS Software

Kamil Kaygusuz [1,2,*]

[1] Karadeniz Technical University, Department of Chemistry, Trabzon, Turkey
[2] Hasan Kalyoncu University, Mechanical Engineering, Gaziantep, Turkey

Accepted 17 December 2022

Abstract

Dual source heat pump systems comprise of a main cold source heat pump that is supported by an additional heat source. Two arrangements have been studied in detail: air source heat pumps combined with solar collectors; and ground source heat pumps coupled with solar collectors. In addition to a situation where solar collectors are devoted solely to direct heating, the solar system can be used with the heat pump in either a series or a dual source scheme. When set up in series, a higher COP can be achieved, but there is often a lower free energy fraction. This is due to the lack of direct solar heating, meaning that auxiliary energy is required more frequently. A careful analysis of all the plant elements, including location, heating and cooling demand, solar collector area, thermal ground probe length, etc. is fundamental for achieving the best outcome in terms of both good primary energy savings and profitable economic performance.

Keywords: Solar energy; Heat pumps; Energy storage; 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, it is possible to better integrate these different electricity-producing and electricity-consuming devices [1-3]. 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 [4-7]. 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]. 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 [8-10].

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 [11-13]. 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

* Corresponding author:
Email: kamilk@ktu.edu.tr

performance of the conventional solar system under cloudy conditions and the low capacity of the heat pump in cold weather [14-21].

2. Solar heat pump system

2.1. Introduction

Solar heat pump systems (SHPs) are hybrid systems in which (electric) heat pumps are combined with solar thermal, solar photovoltaic, or both. While solar thermal collectors convert solar energy into thermal energy, solar photovoltaic panels provide electric energy to the system. Solar thermal collectors can be used either in parallel or in series with heat pumps. In parallel systems (Figure 1), both solar collector and heat pump provide heat for the loads either directly or via the store, while in series (Figure 2), heat from the solar collector is used indirectly as the heat source for the heat pump evaporator.

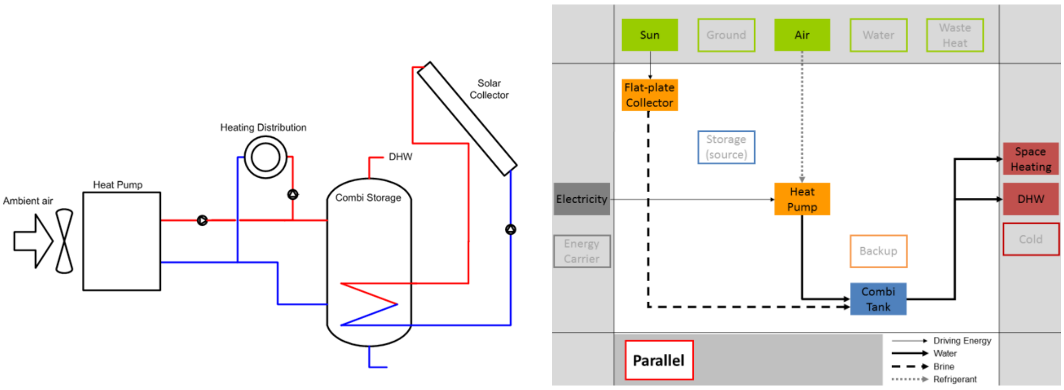


Figure 1. Parallel configuration: hydraulic scheme (left) and square view chart (right) [2]

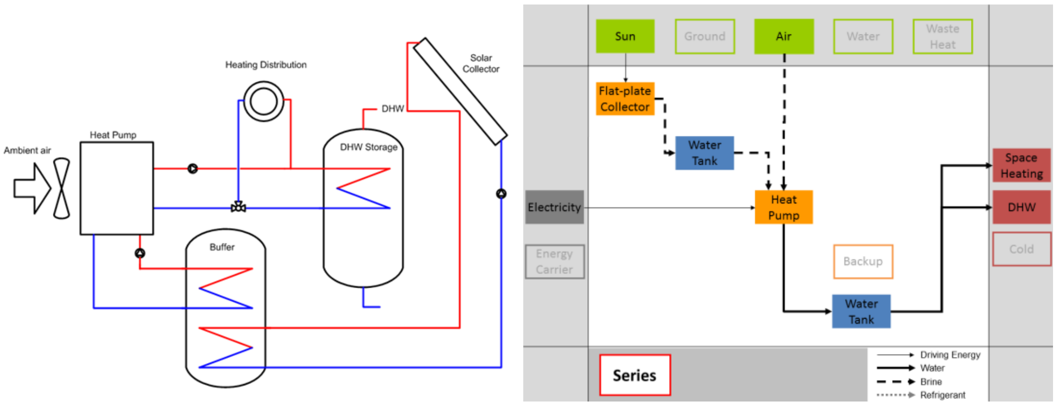


Figure 2. Configuration in series: hydraulic scheme (left) and square view chart (right) [2]

Parallel configuration is simpler in design, installation and control and, furthermore, is more energetically efficient when radiation is high enough. Solar thermal collectors are dived into two main categories: 1) covered or glazed and 2) uncovered or unglazed. At temperature levels typical for space heating (SH) and domestic hot water (DHW) preparation, covered collectors have higher efficiencies compared to uncovered collectors thanks to their transparent cover that reduce heat losses to environment. Covered collectors are divided into flat plate collectors and evacuated tube collectors. Flat plate collectors in parallel to heat pump represent state of the art for this type of systems for residential heating applications [2].

Research and development in the solar-assisted heat pump (SAHP) field have 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. 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 [1-4]:

- 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.

Table 1. Theoretical performance of the dual-source heat pump system for heating season

Months	Number of working days of the HP	Actual Heat Pump COP	Average outdoor Air temp. (°C)	Solar Radiation (MJ/m^2.day)	Collector Efficiency (%)	Percent of heating load supplied by the HP (%)
November	30	3.34	14.8	6.24	74	80
December	30	3.12	10.6	4.74	72	76
January	30	2.96	6.8	5.12	65	50
February	28	2.84	5.7	8.06	60	40
March	30	2.94	7.5	6.94	64	76
April	30	3.20	11.8	11.84	66	86
May	20	3.31	15.9	16.62	68	92

2.2. 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. Table 1. Theoretical performance of the dual-source heat pump system for a heating season.

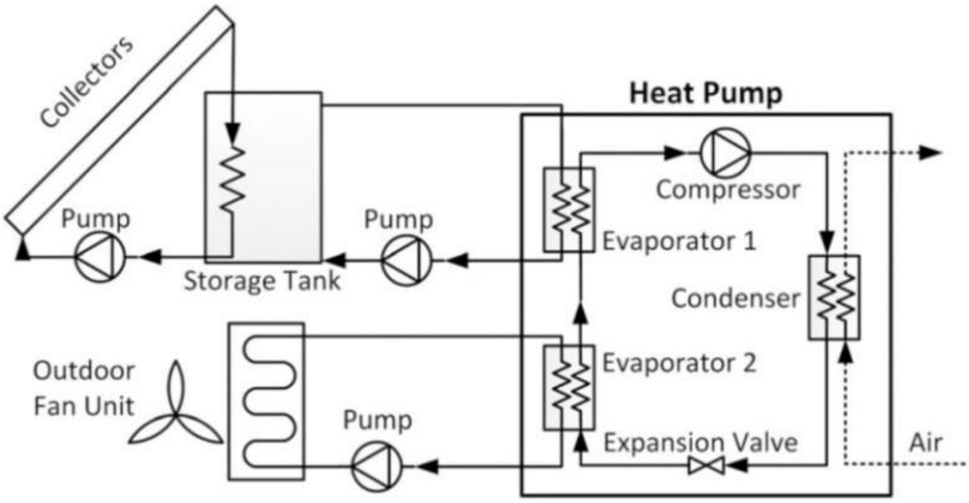


Figure 3. Schematic of a dual source heat pump system (air + solar)

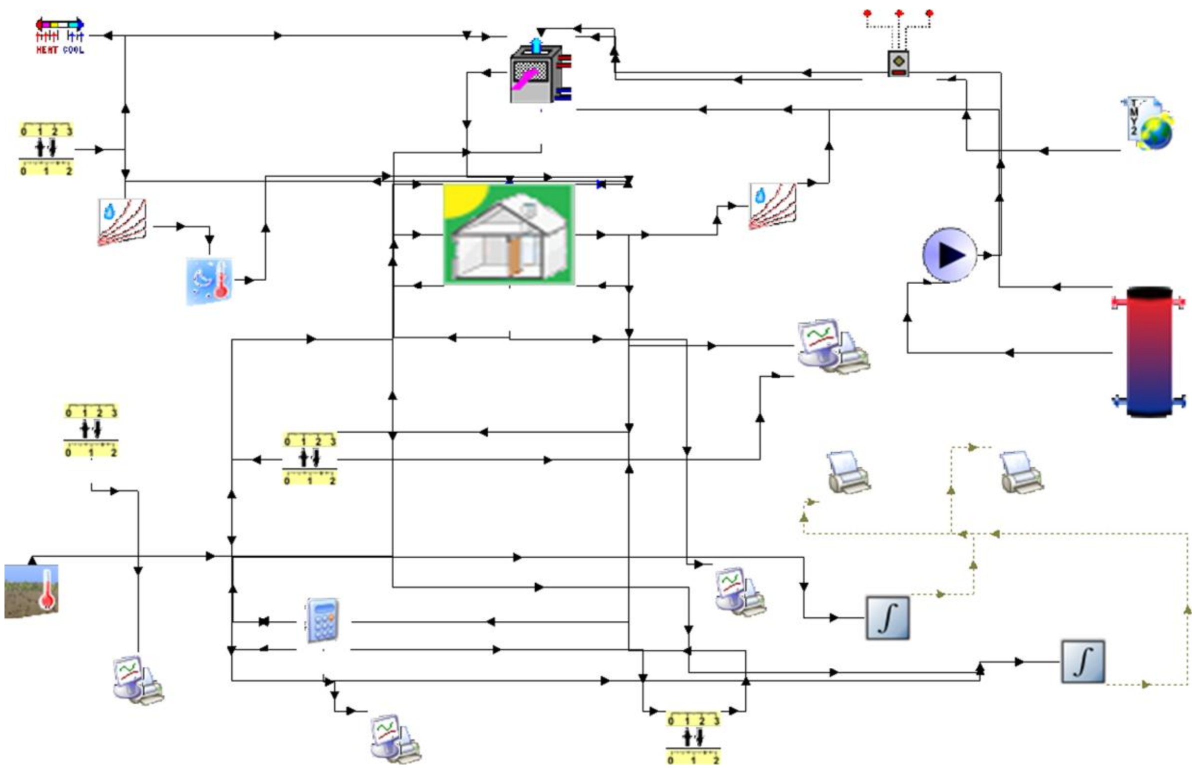


Figure 4. Information flow diagram on TRNSYS

2.3. 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].

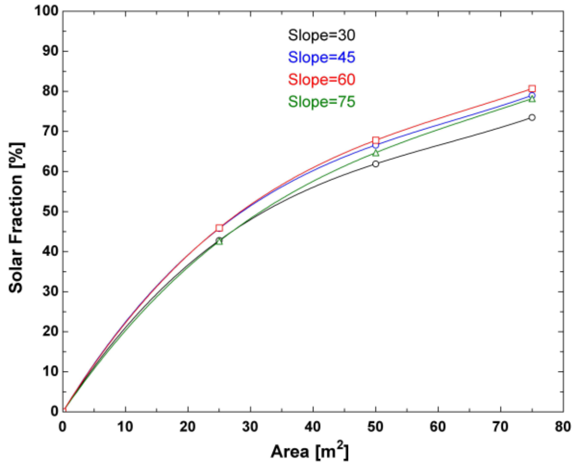


Figure 5. Solar performance according to collector area and slope

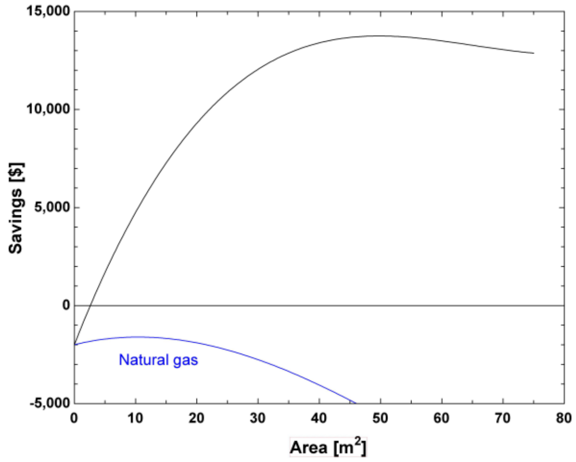


Figure 6. Solar Savings depend on solar collector area

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. 4-10).

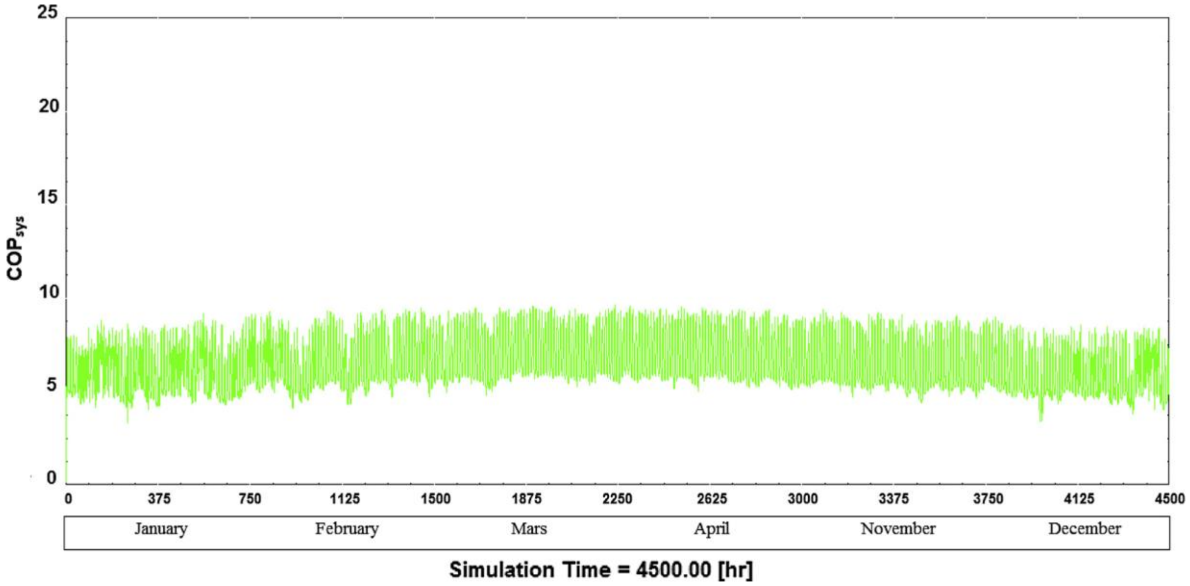


Fig. 7. Theoretical COPsys of the system in heating mode

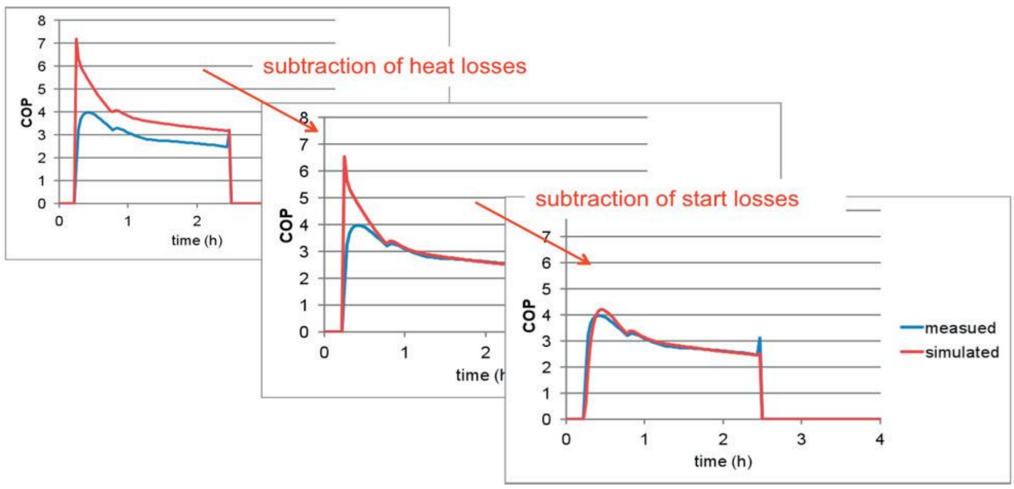


Figure 8. A dynamic model of a heat pump

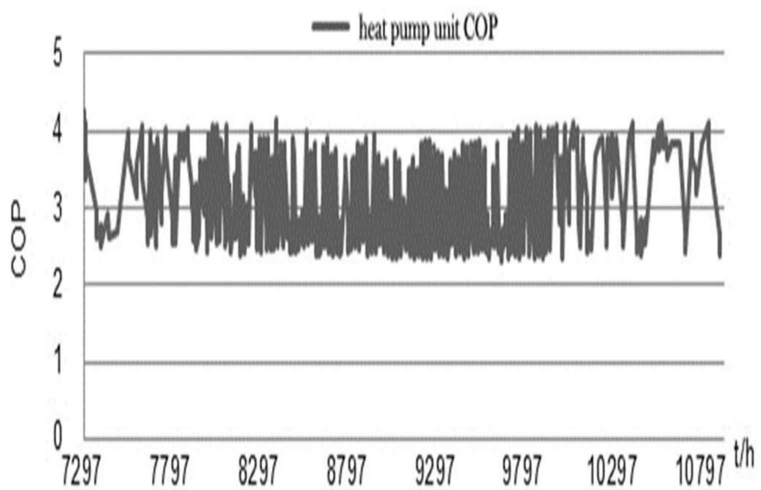


Figure 9. The dual-source heat pump COP hourly variation in the heating season

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.

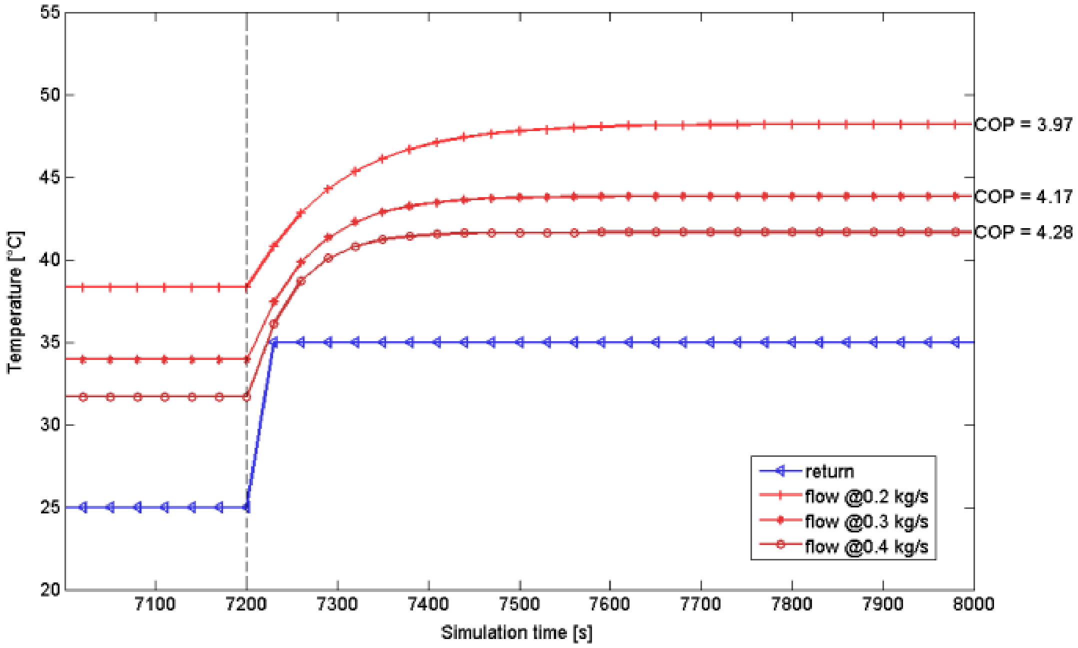


Figure 10. Outlet temp. and COP for a given step of the inlet temp

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].

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

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

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

Due to the factor that the integrated solar heat pump system absorbs the energy not only from collectors but also from air-con rooms, the life cycle savings is positive even at lower collector area, where it is negative for conventional single function solar system. The evaporator-collector makes use of two-phase heat transfer processes, where the temperature of the fluid remains constant. The optimum collector area is also affected by the point at which the fluid reaches superheat region due to the fact that the collector efficiency of single phase region is much lower than that of two-phase region. This optimization makes it possible for the integrated solar heat pump system to be commercialized in different industrial and domestic applications.

When the sun is shining, the collectors will be the primary source of energy for the domestic hot water preparation and for 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. 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. Figure 5 shows the solar performance according to collector area and slope. As shown in Figure 5, the solar fraction increased with the collector area as expected. But, the maximum solar savings are around 40 m^2 collector area as shown in Figure 6. The TRNSYS simulation results are shown in Fig. 7. As shown in this figure, we show that the theoretical COPsys of the system are about between 4-7.

The nature and performance of a dual source heat pump system must be carefully considered when a building is heated by a heat pump combined with solar collectors. The addition of solar collectors can result in lower costs attributed to the ground thermal probes, as it may be possible to reduce the length of probes required. Moreover, solar collectors can recharge the ground in summer when the cooling demand is low, preventing possible overheating of the solar collectors. It is also important to take into account pumping costs within the primary energy analysis, as increased pumping costs may reduce the financial advantages of a dual source system, particularly in mild climates.

Acknowledgment: The authors are greatly acknowledged by the Turkish Academy of Science for financial support for this study.

References

[1] Chargui, R., Sammouda, H. Modeling of a residential house coupled with a dual source heat pump using TRNSYS software. Energy Convers management 2014; 81: 384-399.
[2] Hadorn, J.C. Solar and heat pump systems for residential buildings. Berlin: Ernst & Sohn, 2015.
[3] Duffie, J.A., Beckman, W.A. Solar engineering of thermal processes, Fourth Edition, New Jersey: John Wiley & Sons, 2013.
[4] Freeman, T.L., Mitchell, J.W. Audit, T.E. Performance of combined solar-heat pump systems, Solar Energy 1979; 22: 125-135.
[5] Klein SA, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, et al. TRNSYS 16 – a transient system simulation program. Madison, USA: Solar Energy Laboratory, University of Wisconsin; 2006.
[6] Kaygusuz, K. Performance of solar-assisted heat-pump systems Applied Energy 1995; 51: 93–109.
[7] Kaygusuz, K. Investigation of a Combined Solar-Heat Pump System for Residential Heating. Part 2: Simulation Results. Int. J. Energy Research 1999; 23: 1213–1223.
[8] Kaygusuz, K., Ayhan, T. Experimental and theoretical Investigation of Combined solar heat pump system for residential heating. Energy Convers Mgmt 1999; 40: 1377-1396.
[9] Kaygusuz, K. Experimental and Theoretical Investigation of a Solar Heating System with Heat Pump. Renewable Energy 2000; 21: 79-102.
[10] Lazzarin, RM. Dual source heat pump systems: operation and performance, Energy and Buildings, 2012; 52: 77-85.
[11] Sauer, HJ. Howell, RH. Heat pump systems, New York: John Wiley and Sons, 1983.
[12] Kaygusuz, K. Performance of solar assisted parallel and series heat pump systems with energy storage for building heating. J. of Eng. Res. Applied Science 2018; 7(1): 759-764.
[13] Kaygusuz, K. Second law of thermodynamics and heat pumps for domestic heating. J. of Engineering Research and Applied Science 2017; 6(2): 668-679.
[14] Kaygusuz, K. Dual source heat pump systems: operation and performance. J. of Engineering Research Applied Science 2020; 9 (2): 1546-1554.
[15] IEA, International Energy Agency. IEA SHC Task 44. Position Paper: Solar and Heat Pump Systems IEA SHC Task 44: Position Paper. September, 2014
[16] Karagiorgas M, Galatis K, Tsagouri M, Tsoutsos T, Botzios-Valaskakis A. Solar assisted heat pump on air collectors: A simulation tool. Solar Energy 2010; 84:66-78.

[17] Banister CJ, Collins MR. Development and performance of a dual tank solar-assisted heat pump system. Appl Energy 2015; 149: 125-32
[18] Lerch W, Heinz A, Heimrath R. Direct use of solar energy as heat source for a heat pump in comparison to a conventional parallel solar air heat pump system. Energy Buildings 2015; 100: 34-42.
[19] Dott R, Genkinger A, Afjei T. System Evaluation of Combined Solar & Heat Pump Systems. Energy Procedia 2012; 30: 562-70.
[20] Poppi, S. Solar heat pump systems for heating applications. Doctoral Thesis 2017, Royal Institute of Technology, Department of Energy Technology, Stockholm, Sweden.
[21] Shaochun, Y. An integrated solar heat pump system for cooling, water heating and drying. PhD-Thesis, Dep. of Mechanical Engineering, National University of Singapore, 2009.