Energy Equip. Sys./ Vol. 6/No. 3/Sep. 2018/ 279-292

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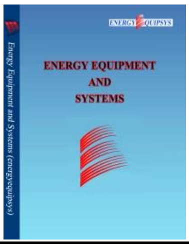

Economic optimization and comparative study of solar heat pumps

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Article history:

Received : 10 October 2017
Accepted : 29 May 2018

ABSTRACT

In this paper, an economic study of solar heat pumps and an investigation of differences between solar heat pumps and conventional heat pumps—based on their performances and energy consumption—are conducted for a residential apartment located in Austin, Texas, USA. Heating in the apartment is provided via a solar heat pump during the cold months of a year. Solar collectors are used to meet the domestic hot water requirement of the apartment during the other months. In order to carry out a rational comparison, the base system comes with an air-to-air domestic heat pump and a boiler to provide domestic hot water. The comparison includes both energy consumption (fuel and power) and economic aspects. The simulation is performed through the commercial software TRNSYS, in which optimization offers a collectors' surface of 28 square meters. The proposed configuration requires almost half of the electrical energy that the conventional system consumes. Its fuel consumption is about a quarter of the non-solar system, which offers a double value of COP in comparison with the traditional system. The economic calculations reveal that the payback period is about two years.

Keywords: Solar Heat Pump, Solar Heating, TRNSYS, Economic Analysis, Optimization.

1. Introduction

Considering the depleting potential of non-renewable sources of energy and fossil fuels, solar energy has been regarded as a source for providing domestic hot water and space heating of residential sections [1]. In many cases, direct usage of solar energy for space heating is uneconomical, since solar collectors' efficiency is highly dependent on their operating temperature. In other words, as the temperature of the inlet fluid to the collector goes up, the collector becomes inefficient. This inefficiency imposes extra surface on the collectors or a need for highly effective collectors, both of which are costly [2]–[4]. An alternative for providing heating requirements may be solar heat pumps [5]. In this approach, the solar heat utility is not directly used but it increases the evaporator's pressure as solar heat is absorbed. This results in an increase in the system COP [6][7].

Numerous studies have been conducted on solar heat pumps. Lerch et al. [8] were the first researchers who studied a combination of heat pumps with solar energy. Their innovated combination, which utilizes solar heat as a heat source, is compared with traditional heat pumps. They also compared the seasonal performance factor, solar fraction, and heat

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pumps' performances for different collector areas. Li et al. [9] investigated the combination of heat pumps and solar heat orientation to provide space heating and hot water supply in a cold climate. They simulated the system through TRNSYS and compared the proposed configuration's results with those of a traditional one. They considered various modes within the solar system including a water-to-air heat pump, an air-to-air one, and hot water supply. Their results revealed that during heating season, the solar system's COP becomes 3.6, while it is 3.2 for the typical system. They also claimed that the proposed system improved the monthly rate of energy savings to about 52 percent, which showed high potential of the system in energy consumption reduction. During heating seasons, Liu et al. [10] investigated the implementation of the solar heat pumps in order to provide space heating utility in Daqing, China. Here, the collector's efficiency and solar fraction were estimated to be 51 percent and 66 percent respectively. They compared the results of their system and that of a boiler-aided conventional system. Their system offered a total cost of 18 RMB/m2 (RMB is the currency of China), which is due to a 55 percent reduction in energy consumption in comparison with their base case. They also optimized the collector's outlet temperature considering both space heating and hot water supply. Carsen et al. [11] considered the integration of a heat pump and a collector in providing hot water supply, and compared numerical results with experiments outcomes. Within their TRNSYS-simulated system, the solar source was connected to the storage tank via a heat pump and a heat exchanger. Similarly, Chargui et al. [12] investigated the potential advantages of implementation of the combined solar and heat pump system for a building in Tunisia. They investigated their model during a 24-hour period in January and 4500 hours of heating season. Their results offered a highly beneficial COP between 6 and 9. Sterling et al. [13] simulated three different hot water-providing systems in TRNSYS and compared them from the point of view of energy saving. Among the three systems, which are a solar heat pump, traditional solar heating systems using collectors, and an electrical system, the first one was more energy-efficient and economical. Martin Kegela et al. [14] also investigated a coupling solar energy with air and water source heat pumps, and compared their performances and costs with air source and ground source heat pumps for a residential house in Montreal, Canada. They found that solar air source heat pumps needed lower capital costs and they had the highest energy saving compared to air source heat pumps, which means they improved energy savings. S.K. Chaturvedi et al. [7] used a direct expansion solar-assisted heat pump system (DX-SAHP) for providing hot water at low temperatures. Their results showed that this system is ideal for both economic and energy consumption issues compared to heating water only with electricity.

In this study, an economic investigation of solar heat pumps is conducted. Therefore, the solar heat pump is compared with a base case, which includes a typical heat pump and a boiler to provide the hot water supply. The investigated solar heat pump is designated to provide the space heating of a residential building during heating season. The collectors of the component also provide the hot water supply during other months of the year. In this economic study, the life cycle solar saving (LCS) method is considered. The LCS-driven objective function proposes an optimization for which the optimum collectors' area is calculated. Considering the optimum case, a thorough economical study is performed where the payback is one of the results.

Nomenclature

$\dot{Q}_u$	The useful energy gain of the collector	[kJ/hr.]
A_c	The collector area	$[m^2]$
$F_R(\tau\alpha)_n$	The efficiency with which solar radiation is absorbed by the plate and removed by fluid flowing through the collector	[ ]
I_t	The total amount of solar radiation incident on the plane of the collector surface	$[kJ/hr.m^2]$
ΔT	A temperature difference	[ºC]
$F_R U_L$	The collector loss rate	[ ]
$\dot{m}_{fluid}$	The mass flow rate of fluid flowing through	[kg/hr.]

	the collector at any given time	
T_{in}	The temperature of fluid exiting the collector array	[ºC]
$T_{desired}$	The desired (user-defined) temperature at which fluid should exit the collector array if possible	[ºC]
$C_{P,fluid}$	Heat capacity of the heat transfer fluid	[kJ/ (kg. K)]
T_{out}	Temperature of fluid exiting the collector	[ºC]
$\dot{Q}_{tot,heat}$	Total heating power of the heat pump	[kJ/hr.]
$\dot{Q}_{absorption}$	Amount of energy absorbed from the outdoor air stream by the heat pump (heating mode)	[kJ/hr.]
$\dot{P}_{comp}$	Compressor power	[kJ/hr.]
$\dot{P}_{Fan.outdoor}$	Power drawn by the outdoor fan	[kJ/hr.]
$\dot{P}_{Fan.indoor}$	Power drawn by the indoor fan	[kJ/hr.]
COP	Coefficient of performance of heat pump	[ ]

2. System description

The studied residential building, which is 150 m^2, is located in Austin, and it is assumed that four people live in it. The building has also been simulated in Carrier by which air conditioning requirements during different months of a year and peak load conditions are calculated [15]. The simulation reveals that the considered building requires 17 kW of power in the coldest month of the year (January). Figures 1 and 2 show a simplified schematic view of the solar and the typical systems.

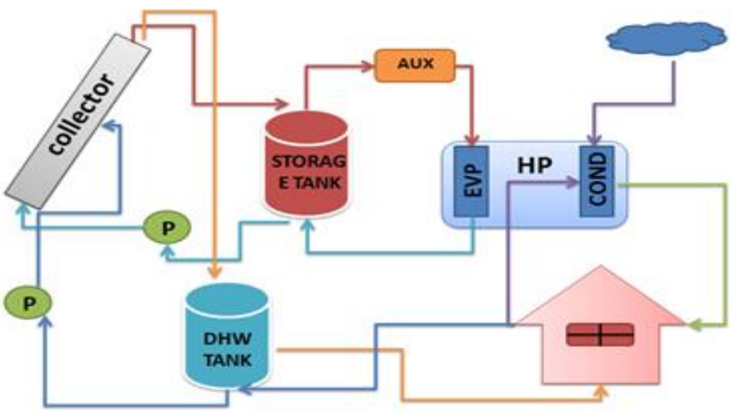

Fig.1. Schematic view of the solar system

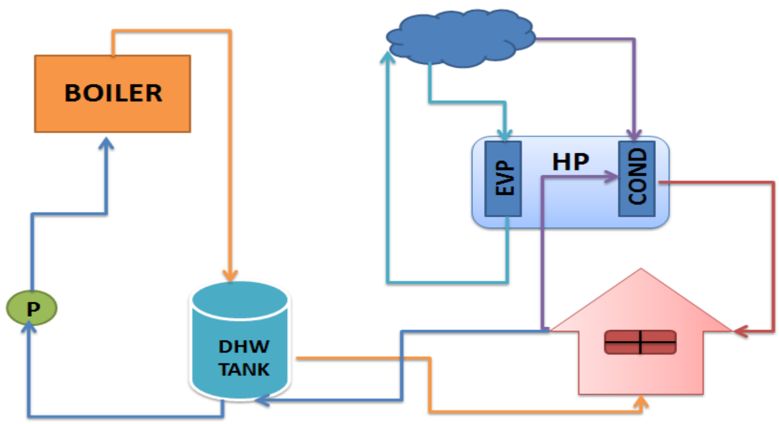

Fig.2. Schematic view of the non-solar system (base case)

As can be seen in Fig.1, to provide space heating a combination of a solar collector and a water-to-air heat pump is employed. The collectors are also responsible for providing the hot water supply to the system. In Fig.2, a schematic of the considered base case is exhibited. As can be seen in the figure, the heat pump satisfies the space heating requirements and a boiler provides the domestic hot water supply. Both systems shown in Figures 1 and 2 are simulated precisely and in detail in TRNSYS.

3.Modeling

3.1. Solar system

As mentioned above, the solar heat pump covers the space heating requirements during heat seasons (late October until early March) and the solar collector provides hot water supply during other parts of the year. The heating loads, including space heating and hot water supply extracted from Carrier, are given as an input to the TRNSYS software. The scheme of the described system is illustrated in Fig.3 and the applied components are listed in Table 1.

The solar system, which is supposed to be installed in Austin, includes three sections which are explained as follows:

- First section:

The first section in this configuration is the solar system, the collectors of which are selected to be flat. This selection is due to the fact that they are less expensive in comparison with evacuated tube collectors. As far as heat pumps are able to operate with low temperature heat sources like that of flat plate collectors, the choice can be appropriate in the system [4]. The water temperature increases to 25°C in the collector and is stored in a storage tank which enhances the system to work during cloudy weather and at night.

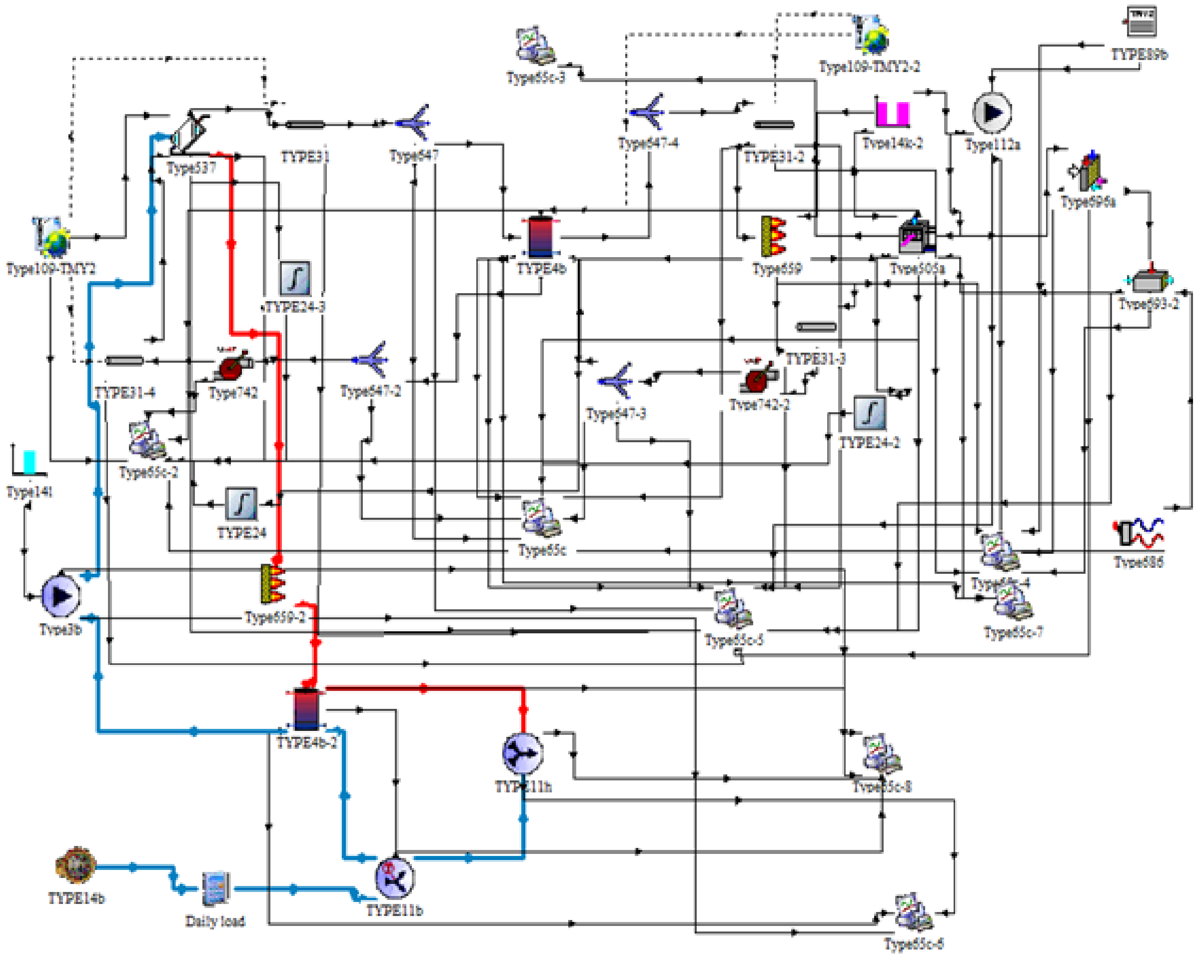

Fig.3. The scheme of the simulated solar system in TRNSYS

Table 1. The components included in the simulated solar system

Component Name	**TRNSYS TYPE**
Weather data reading and processing	TYPE109-TMY
Weather data reader	TYPE89b
Solar flat plate collector	TYPE537
Hydronics/pipe-duct	TYPE31
Hydronics/diverting valve	TYPE647
Stratified storage tank	TYPE4b
Variable speed pump	Type742
Forcing function heating season	Type14K
Auxiliary fluid heater with proportional control	TYPE659
Water loop heat pump/ Water-to-air heat pump	TYPE505a
Air stream conditioning device	Type696a
Load imposed on an air stream	TYPE693
Synthetic building load generators	TYPE686
Fan/single speed	TYPE112a
Quantity integrator	TYPE24
Online plotter	TYPE65
Equation	Equa
Forcing function cooling season	TYPE14l
Forcing function water draw	TYPE14b
Pump/single speed	TYPE3b
Tempering valve	TYPE11b
Tee-piece	TYPE11h

- Second section:

Within the second section, the tank outlet enters an auxiliary heater, which delivers energy to water when required. The process keeps the temperature constant at the inlet of the heat pump's evaporator.

The selected heat pump is water-to-air [16] [17] and water enters the colder end of the tanks from which it passes to the collectors via corresponding pumps and valves. On the other side of the heat pump, 85 percent of the return air mixed with 15 percent of fresh air enters the condenser and receives its required amount of energy, and finally flows to TYPE696a. This component works as an air-handling unit in which its humidity and temperature are set and finally the conditioned air circulates in the place. Both the described sections include different control components to compute the heating time.

- Section three:

This section is related to the generation of hot water during the other months of a year, which are defined in the system through time controllers. At first, the amount of water consumption for four people is calculated via TYPE14b. Cold water enters the tank, from which it is sent to the collectors where the water temperature rises to 55°C. The hot water gets into the tank at the hot part, which is mixed with a small amount of cold water to be delivered to the consumers at 50°C.

3.2.The non-solar system (base case)

The simulation of the typical system considers similar heating load during the same heating season. The domestic hot water data of this base case, which is now generated via a boiler, is assumed to be similar to that of the solar system. The configuration of the simulated system in TRNSYS is illustrated in Figure 4. The components included in the base case are identical to those of the solar system. The two differences are related to the utilized heat source for production of the domestic hot water and the types of the heat pump, which is now air-to-air in the base case. The applied components in the base system are listed in Table 2.

The typical system includes two sections:

- First section

Space heating in this configuration is provided by an air-to-air heat pump in which air exchanges energy with the heat transfer fluid flown within the tubes of evaporator as well as condenser[16][17]. A mixture of 85 percent returns air and 15 percent fresh air absorbs the condenser's heat.

- Second section

The production of the hot water supply is the same as the solar system. The only difference between the two mentioned systems is that the base case employs a boiler instead of the collectors.

- The typical system includes two sections

First section: Space heating in this configuration is provided by an air-to-air heat pump in which air exchanges energy with the heat transfer fluid flown within the tubes of

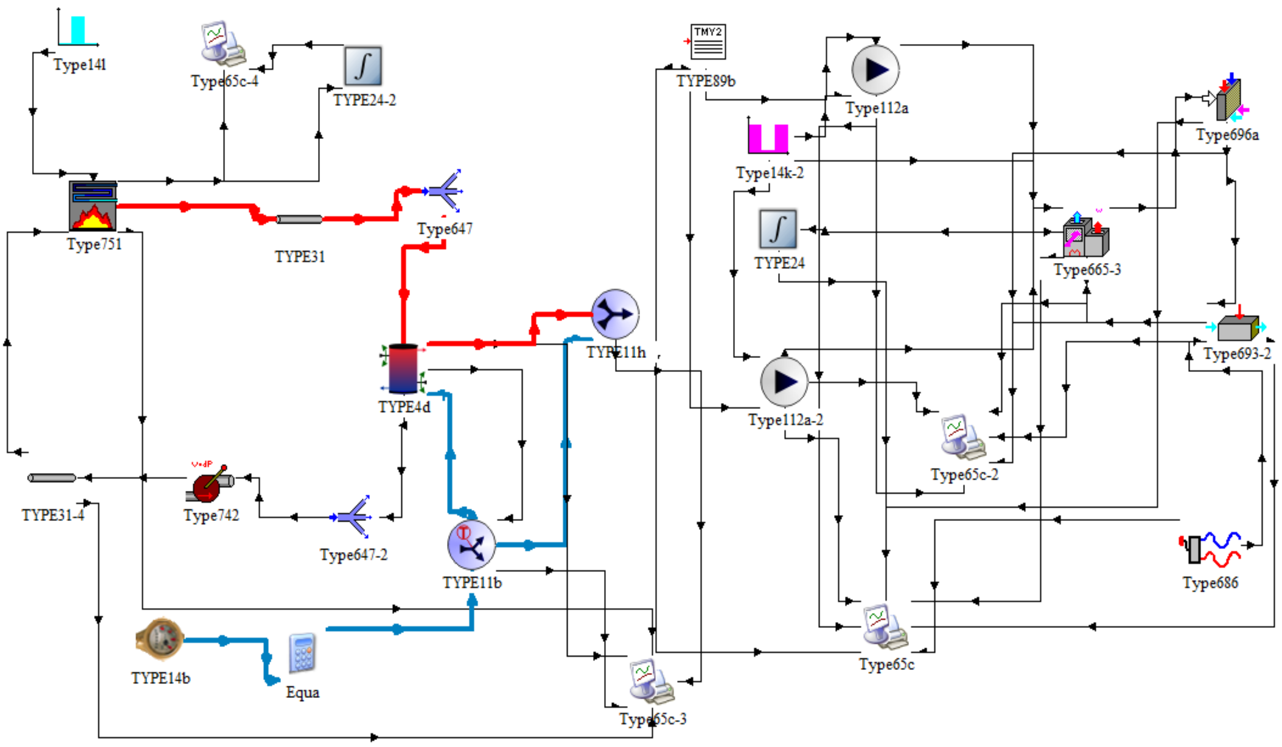

Fig.4. The configuration of the simulated base case in TRNSYS

Table 2. The components used in the typical system but not in the solar one

Component Name	TRNSYS TYPE
Air-to-air heat pump	TYPE665-3
BOILER	TYPE751

evaporator as well as condenser[16][17]. A mixture of 85 percent return air and 15 percent fresh air absorbs the condenser's heat.
Second section: The production of the hot water supply is the same as the solar system. The only difference between the two mentioned systems is that the base case employs a boiler instead of the collectors.

3.3.Governing equations

In this section, major equations embedded in the software are presented. Therefore, the equations incorporated in the solar collectors are as below:

The collector performance of the component TYPE537 is calculated using Eq. (1):

$$\dot{Q}_u = A_c[F_R(\tau\alpha)_n I_t - F_R U_L \Delta T] \quad (1)$$

The temperature of the fluid leaving the collector is calculated using Eq. (2):

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m}_{fluid} C_{P,fluid}} \quad (2)$$

The collector's efficiency is calculated via Eq.(3), which can be written as Eq. (4) too:

$$\eta = \frac{Q_u}{\mathrm{AI_T}} = \mathrm{F_R}(\tau\alpha)_n - F_R U_L \frac{T_i - T_a}{I_T} \quad (3)$$

$$\eta = a_0 - a_1 \frac{\Delta T}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \quad (4)$$

in which ΔT is the difference between the inlet water to the collector and ambient temperature. The COP of the solar system can be calculated using Eq.(5) [18]:

$$C.O.P = \frac{\dot{Q}_{tot,heat}}{\dot{P}_{comp} + \dot{P}_{Fan.outdoor} + \dot{P}_{Fan.indoor}} \quad (5)$$

4.Economic analysis

In this section, it has been examined whether the solar system is economically justified or not. Therefore, the expenses of both systems are calculated during their life cycle. A rational summation of these expenses also provides a tool for the optimum collectors' array area. In order to study a solar system economically, different methods and criteria are developed:

1- Life cycle cost (LCC)
2- Life cycle saving (LCS)
3- Payback time (PT)
4- Return on investment (ROI)

In this study, the second and third approaches are considered for economic analysis.

The operational costs are paid during the system's operational life while the capital cost is invested at the initiation of the operation. In order to have a summation of the two expenses, a coefficient "present worth factor" is calculated. Therefore, all expenses, including operational and capital ones, can be integrated at the year of initiation and more advantageous systems can be distinguished [4].

The following assumptions are considered for the systems and included in this study (in Austin).

Discount rate (d): 5%
Inflation rate of the fuel (i_f): 9.44%
Inflation rate of power (i_e): 4.5%
Fuel price: $0.563 \frac{\mathrm{dollars}}{\mathrm{m^3}}$
Power price: $0.233 \frac{\mathrm{dollars}}{\mathrm{kwh}}$
Project life: 20 years
Down payment: 20% of the total investment
Eighty percent of the capital investment is covered with a 20-year loan term, which is paid back at an interest rate of five percent.

Electric consumption-related cost, except for pumps and piping cost, are disregarded. It is also assumed that the systems' efficiencies don't diminish as they wear out during operation years.

In order to estimate the capital investment, the data of the GOODMAN, RHEEM, VIESSMANN, and WILO companies are implemented. The cost of the solar system components in the United States are listed in Table 3 [19, 20].

4.1. Economic analysis equations

The capital cost of the system by which the amount of loan can be estimated may be calculated using Eq.(6):

$$C_S = C_a A_C + C_i \quad (6)$$

In the above equation
C_S :Total investment cost of the solar components
$\mathrm{C_a}$:Area-related cost
$\mathrm{C_i}$:Solar system cost independent to the collector's area

Table 3. Cost of different components of the systems in the US [21–25]

system	Component	Company	Price(DOLLARS)
Solar	Collector	VEISSEMANN	890 (for each 2.3 square meter)
Solar	4 water-to-air heat pumps of 18000 Btu/hr. capacity	RHEEM	7883.04
Solar	1200-liter tank with 2 meters height	VEISSEMANN	341.99
Solar	2 pumps of 4.39 GPM capacity	WILO	400
Solar	A fan with 270 CFM capacity	GOODMAN	250
Solar	Auxiliary heater of 0.277 L/s	GOODMAN	989

In order to calculate the costs during years of operation, in the first year of the system initiation, Eq.(7) which presents the worth factor is considered:

$$PWF(N,i,d)=\sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^{j}} = \begin{cases}\frac{1}{d-i}\left[1-(\frac{1+i}{1+d})^{N}\right] if i\neq d\\ \frac{N}{1+i} \quad if \quad i=d\end{cases} \tag{7}$$

where N is the years of effective performance of the system. The amount of required fuel for the boiler to produce hot water supply in the base case is calculated using Eq.(8):

$$m_{fuel,BOILER}=\frac{Q_{boiler}}{\eta_{boiler}LHV} \tag{8}$$

The auxiliary heater's fuel mass flow rate is also calculated using Eq.(9).

$$m_{fuel,aux}=\frac{Q_{aux}}{\eta_{aux}LHV} \tag{9}$$

The amount of annual payment of the loan is given in Eq.(10)

$$Annual\ payment=\frac{M}{\mathrm{PWF}(\mathrm{n_L},0,\mathrm{d_m})} \tag{10}$$

where n_L is the number of years that the load should be paid back, assumed to be 20, M is the amount of loan, and d_m is the interest rate of the loan.

Fuel savings in the first year, which is the saving related to the fuel consumption reduction of the solar system, is presented in Eq.(11):

$$Fuel\ Saving=(m_{f,boiler}-m_{fuel,aux})\mathrm{C_f} \tag{11}$$

$\mathrm{C_f}(\frac{\mathrm{DOLLARS}}{\mathrm{m^3}})$ is the fuel price in the first year and m_f is the amount of fuel burnt in a year.

The power saving of the first can be estimated via Eq.(12):

$$PowerSaving=(power_{nonsolarsys}-power_{solarsys})\mathrm{C_e} \tag{12}$$

$\mathrm{C_e}(\frac{\mathrm{DOLLARS}}{\mathrm{kwh}})$ is the power price and power is designated to the amount of electrical energy that each of these systems requires in a year.

The solar saving of the first year is defined as follows in Eq.(13):

$$Solar\ saving = power\ saving+fuel\ saving - annual\ mortgage\ payment - annual\ maintenance\ cost \tag{13}$$

Using Eq.(14), life cycle solar saving (LCS) over N years can be calculated.

$$Present\ worth\ of\ solar\ saving = -down\ payment+solar\ saving\times PWf(N,i,d) \tag{14}$$ [4]

5-Results

As the capital investment is estimated, one can easily calculate the amount of loan and LCS for the collector, which is a function of the collectors' area. Therefore, an optimization is conducted to obtain the optimum area of collectors.

Considering Fig.5, it can be seen that the amount of LCS approaches its maximum value as the collectors' area equals 28m^2. For this optimum area, the capital investment evaluation reaches $22,325. The details of the optimum system and its comparison with non-solar system are given in Table 4.

The return on investment of the solar system is defined as the time needed for the cumulative solar savings to equal the remaining debt principal on the solar energy system (Fig.6).

Considering the curves given in Fig.6, an intersection between the profit curve and the mortgage balance is observable, which signifies the return of the investment period. This interval for the studied solar system is less than two years. Now the two systems are investigated and compared via energy performance's point of view.

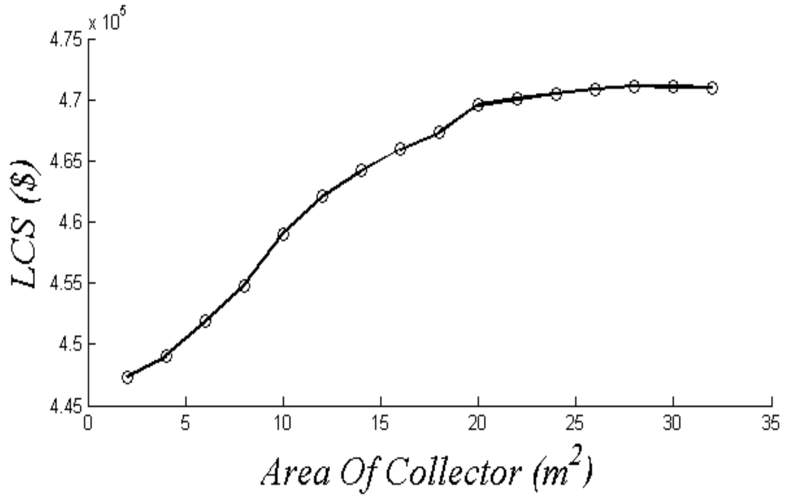

Fig.5. LCS versus the collector area

Table 4. The details of the optimum system

A collector (m^2)	$m_{f,boiler}(m^3)$	$m_{f,aux}$ (m^3)	Power consumption in solar system (kWh)	Power consumption in non-solar system (kWh)
28	22538.31	5410.02	10277.77	22222.22

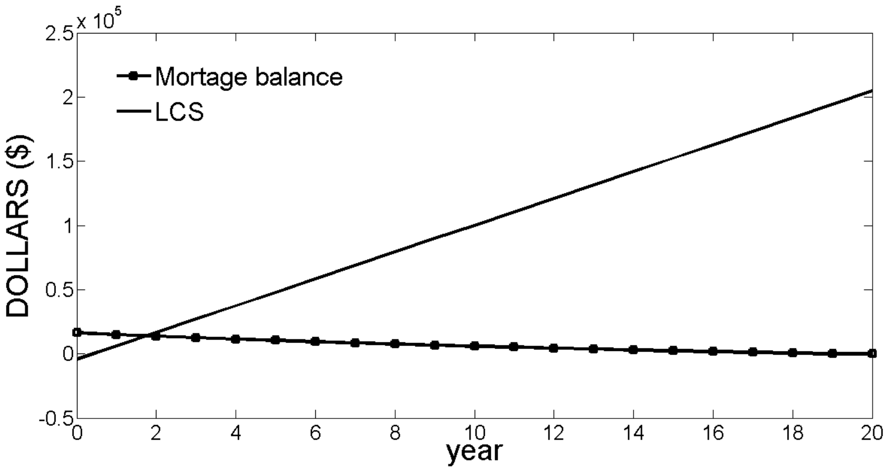

Fig.6. Return on investment for the solar system

1- Comparison among the systems' COP:

As can be seen in Figs. 7 and 8, the solar system's COP varies between 6 and 6.5 while the non-solar system's is within 2.3 and 3.7 interval. It can be concluded that the studied specification of the solar system is almost two times more than the other system. Figure 9 demonstrates yearly averaged comparison between two COPs for systems.

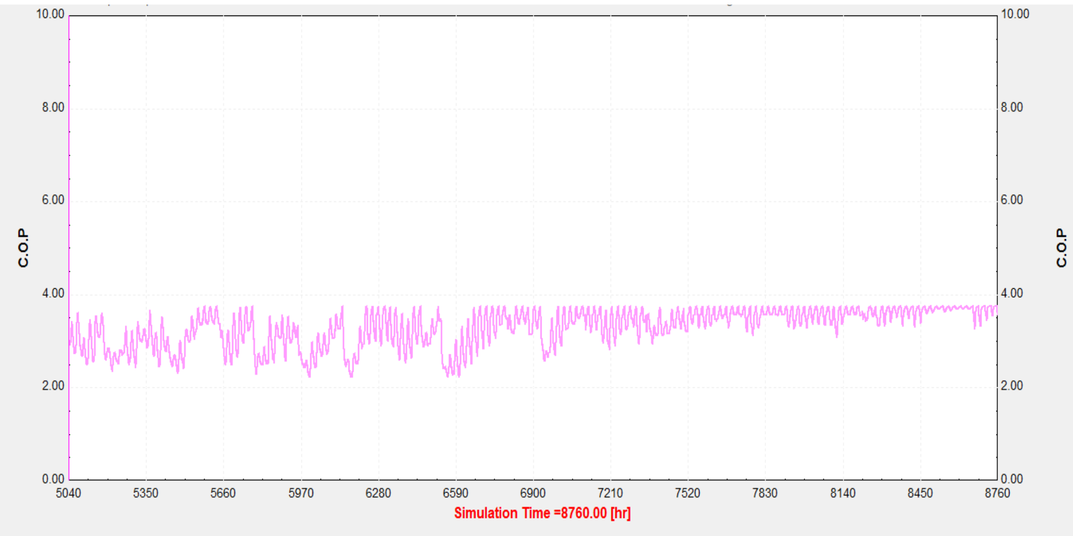

Fig.7. COP of the non-solar system for space heating with an air-to-air heat pump during the heating season

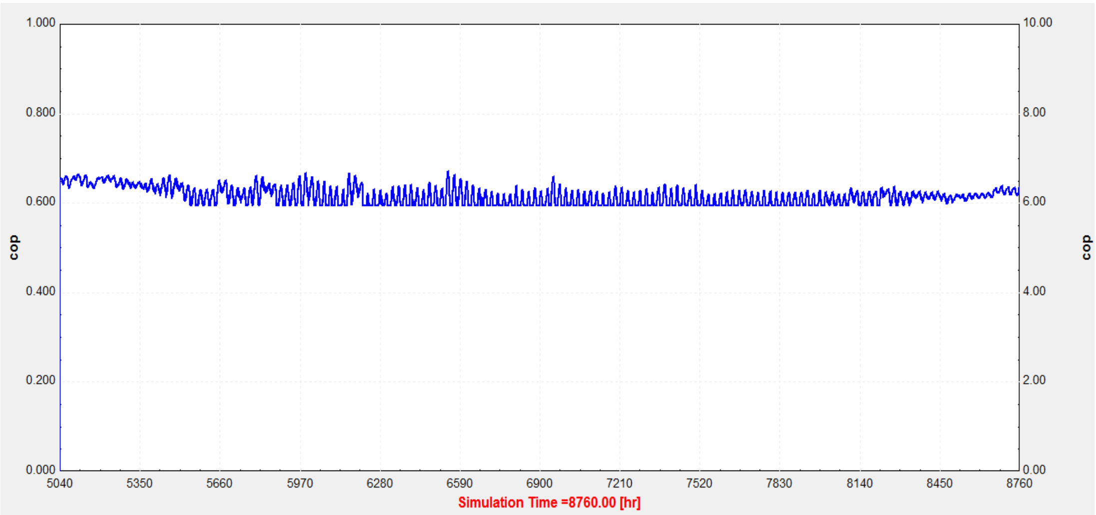

Fig.8. COP of the solar system during the heating season

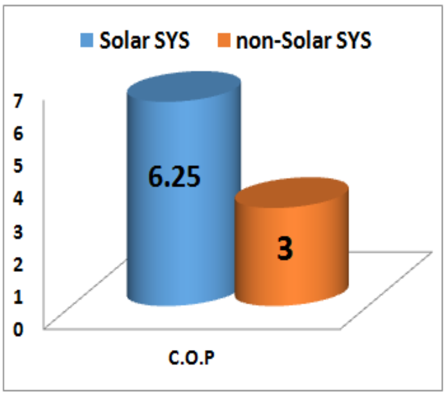

Fig.9. Comparison between the systems' yearly averaged COP

2- Comparison of the power output and compressor's power consumption between the two systems:

As can be seen in Fig.s 10 and 11, the power output of the solar system is less than that of the non-solar one. The solar system's total power varies between 9700 and 10500 kJ/hr, whereas this variation is between 20000 and 23000 kJ/hr. for the non-solar system. The power consumption of the base case is within the 16000–18000 kJ/hr interval while this interval is 9200–9800 kJ/hr. for the solar system. Therefore, the solar system consumes multiple times less than the base case, which works with air-to-air heat pumps. Figure 12 shows the integrated power consumption during the heating season.

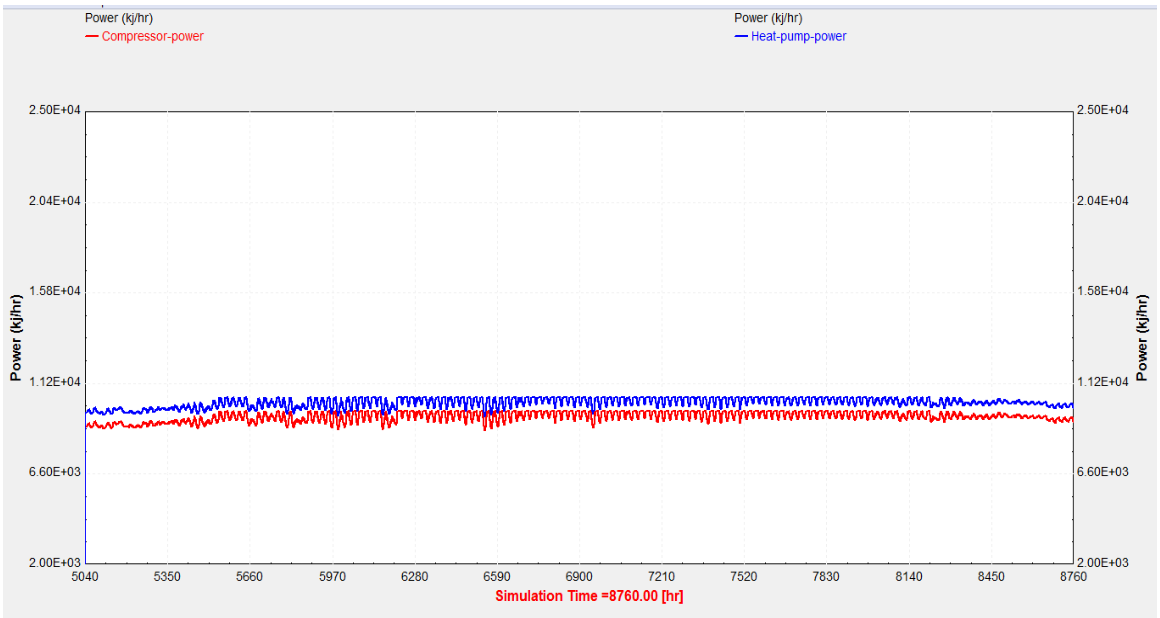

Fig.10. Power output and compressor's power of the solar system heat pump

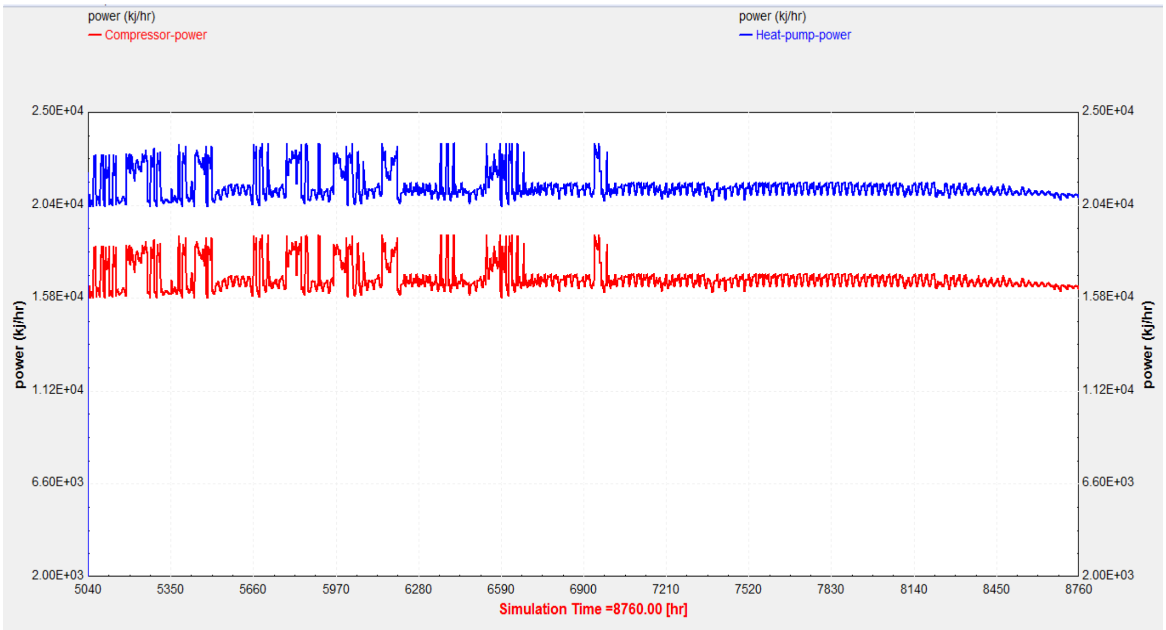

Fig.11. Power output and compressor's power of the air-to-air non-solar system heat pump

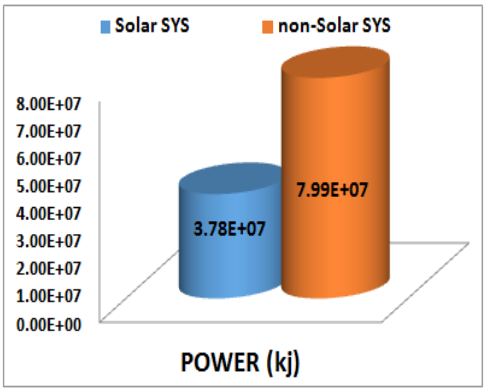

Fig.12. Comparison between the systems' power consumption at the end of the heating season

3- Investigation of the fuel and thermal energy consumption on solar and non-solar systems:

As can be seen in Fig.13, which is extracted from TRNSYS, the largest rate of fuel burning in the solar system is 53000 kJ/hr, while this parameter is 146000kJ/hr. for the non-solar one. This result indicates that the energy consumption of the solar energy due to fuel intake is much less than the non-solar system.

4- Required fuel flow rate in the systems:

As explained above, the fuel consumption for the non-solar system is 22538.31 and this parameter for the solar system is 5410.02. The results are shown in Fig.14.

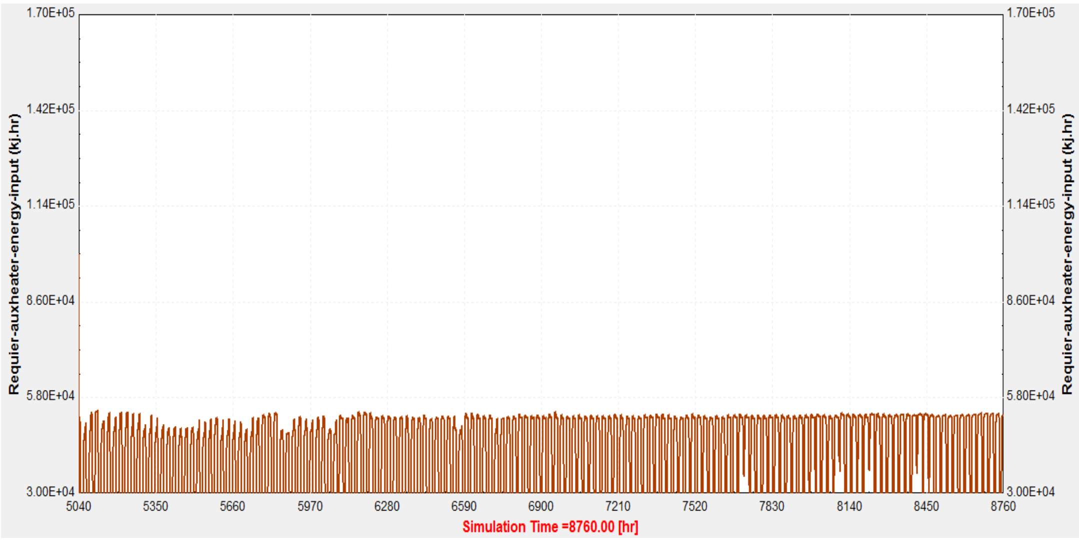

Fig.13. Energy consumption due to fuel burning of the solar system during heating season

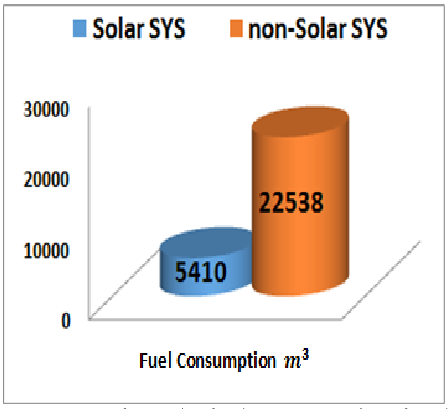

Fig.14. The amount of yearly fuel consumption for the systems

6.Conclusion

As expected, the implementation of the solar system in Austin, Texas, US is justified, whether from the energy performance point of view or economic aspects. Therefore, the considered building is optimum as the collector's array area reaches 28 square meters. Moreover, the simulation revealed that the COP of the system doubles as the solar system is employed. Results showed that the power output of the solar system is approximately half of the traditional system, which means that the solar system reduces the power consumption and its corresponding power cost. The fuel consumption reduction to almost 0.25 of the non-solar system is more attractive since this source of energy is not only expensive but also among non-renewable energy sources.

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