Research Article

Effects of Different Target Solar Fractions on Providing Heat Required for Space Heating, Sanitary Hot Water, and Swimming Pool in Iran: A Case Study in Cold Climate

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Due to limited fossil fuel resources, population growth, and the need to save energy and prevent the emission of pollutants, solar heating is of great importance as a strategic solution. Due to these cases, in the present work, for the first time, the use of flat plate solar water heaters (SWHs) in Shahrekord located in the cold climate of Iran has been studied. The aim is to supply heating for space, sanitary hot water, and swimming pool of a residential apartment. Also, technical-economic-energy-environmental analyses have been done. Three low, medium, and high solar fraction scenarios have been selected for evaluations, and one-year dynamic analysis has been performed by TSOL 2018 commercial software. The required climatic data have been extracted by Meteonorm 7.3 software. The results showed that in most cases of heat supply, i.e., high solar fraction scenario, the percentage of solar heat supply for sanitary hot water, space heating, and swimming pool is 97.8%, 22.3%, and 44.3%, respectively, and the total solar fraction is 41%. Also, in this case, the release of more than 4 tons of CO2 pollutants has been prevented. Energy balance diagrams for different scenarios showed that 60% of losses are optical and thermal and also the highest rate of losses was related to the swimming pool. The lowest cost of heat generated and the lowest payback time were $0.028/kWh and 11.4 years, respectively, which were related to the high solar fraction scenario.

1. Introduction

Energy consumption reflects the socioeconomic growth rate of any country today [1]. Energy from fossil fuels produces a large number of greenhouse gases, which is the main cause of global warming [2–4]. The effects of global warming can be seen in almost every part of the world [5]. It is predicted that if the current emission rate continues, global warming will increase by 1.5°C at an average surface temperature between 2030 and 2052 [6–8]. Dealing with the undesirable effects of climate change is the biggest concern of society around the world [9–12]. A possible solution is to take benefit of renewable technologies and replace fossil technologies with them [13–17]. Among all renewable energy sources, solar energy is widely available and is present in almost all parts of the world [18–23]. In recent decades, global solar thermal capacity has increased sharply and is now widely used around the world to provide heating and cooling [24–28]. In 2019, solar heating systems generated 479 GW of heat, equivalent to 43 million tons of oil saved, which prevented the release of 138 million tons of CO2 (Figure 1) [30].

Figure 2 illustrates the geographical breakdown of the cumulatively installed solar water heating capacity by the
China had installed a total of 337.6 GW of solar water heating by the end of that year. This rate was significantly higher than any other country and accounted for 70% of the global capacity. For the first time ever, the global cumulative operating solar heat capacity decreased in 2019, which was 1% less than the total of 482 GW last year (Figure 3) [32].

Iran is not only rich in fossil fuels but is also in renewable energy due to the diversity of climate and land area [33]. The solar source in Iran is one of the best sources in the world [17,34]. In the following (Table 1), solar collector installation projects in the last two years in Iran are examined. So far, in none of the previous studies, the simultaneous production of solar heat for swimming pool, space heating, and domestic hot water has been done. Therefore, in the present work, for the first time, a dynamic simulation of the use of SWHs in the cold climate of Iran for all the required heat of a residential apartment (space heating, sanitary water heating, and swimming pool water heating) has been performed. The heat supply required for the swimming pool is the first to be considered in the studies. The simulations were performed by TSOL 2018 software and the climatic data were provided by Meteonorm 7.3 software. Although the present work is a case study, its results can be applied to other locations with similar climates. Also, the methodology of the present work and the way of analyzing the results can be used for any other place in the world.

2. Station and Building under Study

The city under study in the present work is Shahrekord, whose location is shown on the climatic map of Iran [42] and the radiation map of Iran [43] in Figures 4(a) and 4(b), respectively. As can be seen from the figures, it is located in a cold climate with a position of 32° 35′ N and 50° 86′ E and has average radiation of more than 5.1 kWh/m²-day. Shahrekord is the highest center of Iran provinces [44] and, according to the 2020 census, has a population of 204,679 people [45]. The building under study is an 80 m² apartment that has a private indoor pool with a length of 8 m, a width of 4 m, and an average depth of 2 m.

3. Software Used

For one-year dynamic simulation, TSOL 2018 commercial software has been used, which has the ability to supply the required space heat, sanitary water consumption, and swimming pool by SWHs [46]. Design, optimization, and accurate calculation are other features of the software [47]. The software database has 4000 types of collectors, 5000 types of heat generators, 600 types of heat storage tanks, 200 solar heating systems, and 8000 different weather stations [45]. TSOL 2018 software receives the required climatic data from Meteonorm 7.3, which is installed simultaneously with it [37].

4. System under Study and Data Required

The schematic of the system under study is shown in Figure 5. Based on the figure, it is clear that the orientation of solar collectors is at an angle of 32° (equal to latitude) [47] and to the south. The aim is to supply 110 liters of sanitary hot water per day with a temperature of 60°C [37] and to
provides space heating and pool water using SWHs and an auxiliary gas boiler of 25 kW. Also, a 300 liter sanitary hot water tank and a 1000 liter space heating hot water tank have been used [46]. According to the location under study, the period of sanitary hot water required is the whole year and the period of space heating is 8 months (October to May). Solar fraction values of low (35%), medium (50%), and high (65%) were considered for which 8 m² collector, 12 m² collector, and 17 m² collector were used, respectively. The freshwater required for the swimming pool is 50 liters/day and the time period of using the pool is included in the calculations all year round. The lifetime of collectors used is 20 years, the annual interest rate in Iran is 18% [48], natural gas price is $ 0.012/m³ [49], price per m² of SWH is $ 200, amount of allowance for solar heating is $ 0.024/kWh, and operating and maintenance cost is 1% of the total system cost.

5. Governing Equations

The radiation received by the collectors is equal to the sum of the direct and diffused radiation. Direct radiation is received from Meteonorm 7.3 software and for diffuse radiation hitting the surface of the collectors, based on the air filtration coefficient \( k_i \), there are the following equations in which \( \alpha \) is the angle of the solar collector [39]:

\[
0 \leq k_i \leq 0.3: \quad \frac{I_d}{I} = 1.02 - 0.245k_i + 0.0123 \sin \alpha,
\]

\[
0.3 < k_i \leq 0.78: \quad \frac{I_d}{I} = 1.4 - 1.749k_i + 0.177 \sin \alpha,
\]

\[
k_i > 0.78: \quad \frac{I_d}{I} = 0.486k_i - 0.182 \sin \alpha,
\]

where \( I \) is the total radiation on a horizontal surface in terms of kJ/m² and \( I_d \) is the diffused radiation on a horizontal surface in terms of kJ/m².

<table>
<thead>
<tr>
<th>No.</th>
<th>No. of collectors</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>Forest regions of West Azerbaijan</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>Rural areas of Lordegan, Chaharmahal and Bakhtiar</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>Rural areas of Hormozgan</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>Kohgliyeh and Boyer-Ahmad villages</td>
</tr>
<tr>
<td>5</td>
<td>295</td>
<td>Villages of Kermanshah Province</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>100 villages of Zanjan Province</td>
</tr>
<tr>
<td>7</td>
<td>122</td>
<td>Parks in the center of Tehran</td>
</tr>
<tr>
<td>8</td>
<td>41</td>
<td>Marivan and Sarvabad villages, Kurdestan</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>Nomadic areas of Sabzvar, Razavi Khorasan</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>Forest areas of Chaharmahal and Bakhtiar Province</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>Forest areas of Fars Province</td>
</tr>
</tbody>
</table>
Figure 4: Location of Shahrekord on (a) climatic map of Iran [34] and (b) radiation map of Iran [35].

Figure 5: Schematic of the simulated system.
Since some of the radiation received by the collector is wasted, the energy balance is expressed by the following equation [37]:

\[
\rho = G_{\text{diff}} \cdot \eta_0 \cdot f_{IAM} + G_{\text{diff}} \cdot \eta_0 \cdot f_{IAM, \text{diff}} - k_0 (T_{cm} - T_A) - k_\eta (T_{cm} - T_A)^2,
\]

where \(G_{\text{diff}}\) is the direct strike radiation to the collector surface, \(G_{\text{diff}}\) is the diffused radiation striking the collector surface, \(\eta_0\) is the collector efficiency, \(f_{IAM}\) is the direct radiation correction factor, \(f_{IAM, \text{diff}}\) is the diffused radiation correction factor, \(k_0\) is the first-order loss coefficient, \(k_\eta\) is the second-order loss coefficient, \(T_{cm}\) is the average collector temperature, and \(T_A\) is the air temperature.

Also, in the discussion of pollution, it should be noted that the software considers the amount of \(\text{CO}_2\) emission prevention for natural gas fuel consumption equal to 5.14 g/kWh [45]. The parameters of total solar fraction, solar fraction of sanitary water consumption, solar fraction of space heating, and solar fraction of swimming pool are obtained by the following equations, the parameters of which are shown in Figure 5:

\[
\text{total solar frac} = \frac{Q_{S,\text{DHW}} + Q_{S,\text{HL}} + Q_{S,\text{SP}}}{Q_{S,\text{DHW}} + Q_{S,\text{HL}} + Q_{S,\text{SP}} + Q_{\text{AUXH,\text{DHW}}} + Q_{\text{AUXH,\text{HL}}} + Q_{\text{AUXH,SP}}},
\]

\[
\text{DHW solar frac} = \frac{Q_{S,\text{DHW}}}{Q_{S,\text{DHW}} + Q_{\text{AUXH,\text{DHW}}}},
\]

\[
\text{heating solar frac} = \frac{Q_{S,\text{HL}}}{Q_{S,\text{HL}} + Q_{\text{AUXH,\text{HL}}}},
\]

\[
\text{swimming pool solar frac} = \frac{Q_{S,\text{SP}}}{Q_{S,\text{SP}} + Q_{\text{AUXH,SP}}},
\]

In the present work, economic calculations are based on the net present value (NPV) method. This parameter, which is one of the main and most widely used methods of investment evaluation, is calculated by the following equation [46]:

\[
\text{NPV} = R_t - C,
\]

where \(R_t\) is the total revenue and \(C\) is the cost of the SWH system, each of which is calculated by the following equations:

\[
C = C_0 + \sum_{n=1}^{N} C_{\text{O&M}} \times \left(1 + \frac{e}{d}\right)^n,
\]

\[
R_t = \frac{Q_u}{\eta_h} \sum_{n=1}^{N} \left(1 + \frac{e}{d}\right)^n,
\]

where \(C_0\) is the total purchase cost, \(C_{\text{O&M}}\) refers to the total annual operating and maintenance costs, \(d\) is the reduction rate, \(n\) is the number of years, \(\eta_h\) is the efficiency of the auxiliary gas boilers, and \(Q_u\) is the useful energy collected by the SWHs.

### 6. Results

The simulation results for the three scenarios of a low, medium, and high solar fraction are given in Table 3. It is clear from the results that almost a large part of the heating required for sanitary hot water in all scenarios is provided by SWHs and the main difference is in the space heating and swimming pool water heating. In the most possible case, i.e., using 17 m² of flat plate solar collector, 22.3% of the required space heat and 44.3% of the required heat of the swimming pool are provided by solar heating, in which case 18576 kWh of heating is supplied by the auxiliary gas boiler which prevents the release of more than 4 tons of \(\text{CO}_2\) emission. The highest solar fraction with a rate of 41% is related to the scenario of using 17 m² of solar collector and leads to a system efficiency of 33.6%.

Figures 6(a)–6(c) compare the solar heating produced with the total heat required for the three scenarios under study. It is clear from the figures that the highest percentage of heat supply required is in the 4 warm months of the year that there is no need to heat the space. In the cold months of the year, the main need is provided by gas boiler. For the high solar fraction scenario, in July, August, and September, almost all of the 400 kWh/week of heat needs are met by solar heating.

An energy balance schematic for different solar fraction scenarios is shown in Figure 7. This schematic helps engineers to examine different points of the system and identify critical points and help improve the efficiency of the system by trying to solve the problem of heat loss in the solar heating system. The results show that the higher the radiation received, the higher the optical and thermal losses, which is obvious because more radiation is received for more collectors. Another point that can be seen from the results of Figure 7 is the very high percentage of optical and thermal losses, which account for almost 60% of the total received radiation. These losses depend on the type of solar collectors, air temperature, etc., and not much can be done to reduce them. Other major losses occur in swimming pools, and very
Table 3: Simulation results for different scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Solar energy (kWh)</th>
<th>Auxiliary heating (kWh)</th>
<th>CO2 avoided (kWh)</th>
<th>Total solar fraction (%)</th>
<th>System efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DHW</td>
<td>Heating</td>
<td>Swimming pool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>2812 (94.8%)</td>
<td>662 (5.5%)</td>
<td>2355 (15.1%)</td>
<td>24749</td>
<td>1768</td>
</tr>
<tr>
<td>Medium</td>
<td>2924 (96.6%)</td>
<td>1616 (13.4%)</td>
<td>4373 (27.8%)</td>
<td>21876</td>
<td>2725</td>
</tr>
<tr>
<td>High</td>
<td>2983 (97.8%)</td>
<td>2688 (22.3%)</td>
<td>7262 (44.3%)</td>
<td>18576</td>
<td>4037</td>
</tr>
</tbody>
</table>

Figure 6: Produced solar heating compared to the total heat required for solar fraction scenarios. (a) Low. (b) Medium. (c) High.

Figure 7: Continued.
High and serious measures must be taken to reduce them. Losses in storage tanks and piping systems are also in the last ranks of losses.

Economic analysis for different solar fraction scenarios is given in Table 4. The results of Table 4 show that with increasing solar fraction (increasing the number of solar collectors), the price per kWh of solar heat produced decreases and also the payback time decreases. According to the results, the most suitable scenario, which is a high solar fraction, has a price of $0.028 per kWh of generated heat and a return on investment of 11.4 years. The reason for this high return on investment is the low price of natural gas in Iran. Figure 8 shows the economic chart of the top scenario over its 20-year lifetime. According to the figure, at the end of the twentieth year, there will be a profit of $4220.

Table 4: Results of economic analysis performed for the studied scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cost of energy ($/kWh)</th>
<th>NPV ($)</th>
<th>Capital return time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.03</td>
<td>-885</td>
<td>12</td>
</tr>
<tr>
<td>Medium</td>
<td>0.029</td>
<td>-1303</td>
<td>11.7</td>
</tr>
<tr>
<td>High</td>
<td>0.028</td>
<td>-1801</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Figure 7: Schematic of energy balance for different solar fraction scenarios. (a) Low. (b) Medium. (c) High.
7. Conclusion

Despite the geographical location of Iran, which has a very high intensity of radiation, studies in this regard have not been sufficient. In all previous works, only space heating and sanitary water heating were studied, and this is the first time that the pool heating is evaluated for a residential apartment in Shahrekord located in the cold climate of Iran. TSOL 2018 commercial software and Meteonorm 7.3 have been used for one-year dynamic simulation. The results showed the following:

(i) The total solar fraction for low, medium, and high target solar scenarios is 19.1%, 28.9%, and 41%, respectively.
(ii) The lowest amount of auxiliary gas boiler use with 18576 kWh is in the high solar fraction scenario.
(iii) In the high solar fraction scenario, the release of more than 4 tons of CO₂ pollutants is prevented.
(iv) The highest system efficiency is 33.6%.
(v) The highest losses in the studied system are related to swimming pool losses, optical losses, and heat losses, respectively.
(vi) The lowest heat generated cost is $ 0.028 per kWh.
(vii) The minimum return on investment is 11.4 years.

8. Future Works

In the continuation of the present work, all climates of Iran can be evaluated and the effect of using SWHs in different climates can be compared. Also, using ranking methods, it is possible to check all the stations in Iran and find the station that is superior in all aspects of energy, economy, environment, etc. Also, the effect of using different types of solar collector technologies, the effect of using different hot water storage tanks, the effect of work fluid, etc. are among the items that are suggested to be addressed in future works.

### Abbreviations

- **N**: Project lifetime (year)
- **ρ**: Collector energy balance (kW)
- **C**: Cost of the SWH system ($)  
- **e**: Useful life (year)
- **n**: Number of years (-)
- **d**: Rate of decline (%)  
- **NPV**: Net present value ($)  
- **α**: Tilt angle (°)  
- **I**: Total hourly radiation on a horizontal surface (kJ/m²)  
- **SWH**: Solar water heater (-)  
- **Tₐ**: Air temperature (K)  
- **Cᵦ**: Total purchase cost ($)  
- **kᵢ**: Hourly clearness index (-)  
- **Rᵦ**: Total revenue ($)  
- **ηᵦ**: Efficiency of the auxiliary boiler (%)  
- **Cᵦᵦᵦ**: Total annual operating and maintenance costs ($)  
- **Tₑᵦ**: Average temperature of collector (K)  
- **kᵦ**: Quadratic heat transfer coefficient (W/m².K²)  
- **Qₛᵦᵦ**: Solar heating for swimming pool (kW)  
- **Qₛᵦᵦᵦ**: Solar heating for DHW (kW)  
- **Qᵦᵦᵦ**: Solar heating for heating load (kW)  
- **Qᵦᵦᵦᵦ**: Auxiliary heating for swimming pool (kW)  
- **Qᵦᵦᵦᵦᵦ**: Auxiliary heating for DHW (kW)  
- **Qᵦᵦᵦᵦᵦᵦ**: Auxiliary heating for heating load (kW)  
- **Iᵦ**: Hourly diffuse radiation on a horizontal surface (kJ/m²)  
- **Gᵦᵦ**: Part of solar radiation striking a tilted surface (kW)  
- **ηᵦ**: Collector’s zero-loss efficiency (%)  
- **fᵦᵦ**: Incidence angle modifier factor (-)  
- **Gᵦᵦᵦ**: Diffuse solar radiation striking a tilted surface (kW)  
- **fᵦᵦᵦᵦ**: Diffuse incidence angle modifier factor (-)  
- **kᵦ**: Simple heat transfer coefficient (W/m².K)
Q_s: Useful energy collected by the solar collectors (kW).

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

References


