Using nanoparticles in solar collector to enhance solar-assisted hot process stream usefulness

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ABSTRACT

In this study, focusing on building energy usage (BEU) reduction, a solar system was added to HVAC system to reduce its energy demand. The evaluation of the usefulness of incorporating the solar system for three climatic zones in Saudi Arabia (Najran, Sharorah and Taif) was studied. The annual calculations showed that solar collectors filled with water-EG (70:30 wt%) reduced BEU by 14,790 kWh (for Najran), 16,440 kWh (Shrorah) and 12,420 kWh for Tiaf climate regions. This means under the climate of Sharorah, solar collectors were more efficient than others. The addition of CuO nanoparticles improved the performance of collectors in all three regions. In Sharorah, the energy saving in the presence of CuO (at 25 ppm) was calculated to be 18,730 kWh, and with the addition of more alpha, the energy-saving reached 19,440 kWh (at 50 ppm) and 20,430 kWh (at 100 ppm). Finally, it was found that owing to using a solar system equipped with CuO nanoparticles, BEU reduced by 45.1% (for Najran), 35.7% (for Sharorah) and 38.4% (for Taif) under the best conditions.

Introduction

In 2020, the residential sector consumed 6.096×10^{12}kWh energy, while the commercial sector used 4.912×10^{12}kWh. Taking into account the consumptions of 9.106×10^{12}kWh for the industrial sector and 7.120×10^{12}kWh for the transportation section, it is concluded the share of residential + commercial reaches 40.42% [1,65–67]. To decline building energy usage (BEU), two methods can be used, one of which is to reduce the amount of energy passing through the walls [2–4,68–70], and the other way is to use renewable energy [5–7,71–73].

One of the techniques that can lead to less energy consumption in buildings is the use of PCM [8–13,74,75], which has been suggested by many researchers. PCM can act as an insulator; Be a barrier to heat transfer. The reduction in energy consumption in this way has a direct impact on the air conditioning system.

In a numerical study by Li et al. [14], the authors added a layer of PCM with a thickness of 1, 2 and 4 cm to the wall and then compared the heat exchange rate of the base wall (20 cm) by walls containing PCM (21, 22 and 24 cm). Calculations showed that the heat exchange from the base wall was 8.607 kWh (equivalent to 30987 kJ), while the heat transfer from the RT-27 filled walls with a thickness of 21, 22 and 24 cm was 7.569, 6.649 and 5.282. KWh. In other words, PCM was able to reduce the heat exchange by 1.038, 1.958 and 3.325 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$. They changed the installation location of the PCM and found that the closer the PCM installation location to the hottest source, the better its performance. Also, the effect of PCM thickness on the amount of heat exchange showed that the positive effect of PCM reduced with thickness growth. Although the installation of PCM at a thickness of 1 cm reduced the heat exchange by 1.038 kWh, the thickness of 4 cm could not reduce the heat transfer by 4.152 kWh. In other words, in thicknesses 1, 2 and 4, the rate of heat exchange reduction was 1.038, 0.979 and 0.83125 $\frac{\mathrm{kWh}}{\mathrm{m}^2.t_{\mathrm{PCM}}}$ (t is PCM thickness [cm]). The authors [14] investigated the effect of thermophysical properties on the PCM usefulness and showed that thermal conductivity is the most important property. Considering the high conductivity of $CaCl_2.6H_2O$ compared to other PCMs, it was found that the lowest effectiveness is attributed to this PCM. To confirm this claim, the authors compared the thermal behavior of a wall containing $CaCl_2.6H_2O$ with a similar $C_{16}-C_{18}$ filled wall. They considered the melting temperatures of both PCMs to be the same and found that the latter wall was better in reducing heat exchange by 1.0886 kWh. Then, to

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investigate the effect of latent heat, they considered the latent heat of both PCMs to be the same and found that the latter wall, by 3919 kJ (equivalent to 1.0877 kWh), performed better than the former wall. In other words, the heat transfer of the latter wall was 1.0877 kWh less than the former wall. This implies that thermal conductivity is more important than the latent heat enthalpy. The technique of using nanofluid was seen in many studies [15–21,76,77].

Jawed et al. [22] used several solar collectors to supply thermal power for an industrial process to decline energy usage (EU). They examined the solar collator effectiveness (SCE) in two scenarios, water-filled solar collectors and CuO/water-filled one. In the former scenario, they reported a 671 $\frac{kWh}{m^2.year}$ saving energy. In other words, using solar collector (SC), which is supplied with water at 60 $\frac{lit}{hr}$, EU declined annually by 671 kWh per square area. They decided to rise the flow rate to inspect its effect on EU and revealed that saving energy value of 671 $\frac{kWh}{m^2.year}$ changed to 383 at 120 $\frac{lit}{hr}$ and 215 $\frac{kwh}{m^2.year}$ at 240 $\frac{lit}{hr}$. The authors then used CuO to amplify saving energy and they found that it improved by 40.31 $\frac{kwh}{m^2.year}$ at 60 $\frac{lit}{hr}$, 32.55 $\frac{kwh}{m^2.year}$ at 120 $\frac{lit}{hr}$ and eventually 27.52 $\frac{kwh}{m^2.year}$ at 240 $\frac{lit}{hr}$.

In this study, taking into account the climatic conditions of Saudi Arabia, the main goal is to reduce EU in the air conditioning system of the building by focusing on the use of solar energy. Solar systems are able to provide thermal energy and thus can meet the heating requirements well. The proposed HVC system uses a boiler for heating and cooling, so combining it with a solar system is very promising. In this study, by performing an annual analysis, the amount of energy saving for the climates of Najran, Sharorah and Taif is determined. Then, the effect of copper oxide nanoparticles at 25, 50 and 100 ppm on BEU is discussed.

Problem

The use of non-fossil fuels, which emit no greenhouse gases and are, in a way, renewable [23–26], has been observed by many researchers in many phenomena [27]. In this study, to reduce BEU a solar system is added to the HVAC system. Fig. 1 describes the solar system and HVAC system and shows that by combining the solar system with it, EU in boiler can be reduced. To keep warm the building in winter, the system of boiler and fan coil is used. In both cooling and heating system, it seems that by using the solar collector, boiler EU reduces.

Weather information for the two Saudi Arabia cities is shown in Fig. 2. It is observed that the temperature for each region fluctuates in the range of 1–50 °C and its average is equal to 26 °C for Najran, 25.9 °C for the Taif and 28.7 °C for the Sharorah.

Mathematical formulation

Many researchers focused on heat transfer, fluid mechanics and thermodynamic aspects [28–43]. In general, when the solar energy reaches the Earth’s atmosphere, it is divided into two components: the vertical component (beam) and the non-vertical component, which that scientist calls the diffuse component (Fig. 3).

The incident radiation over surface collector is obtained using Eq. (1) [44,45]:

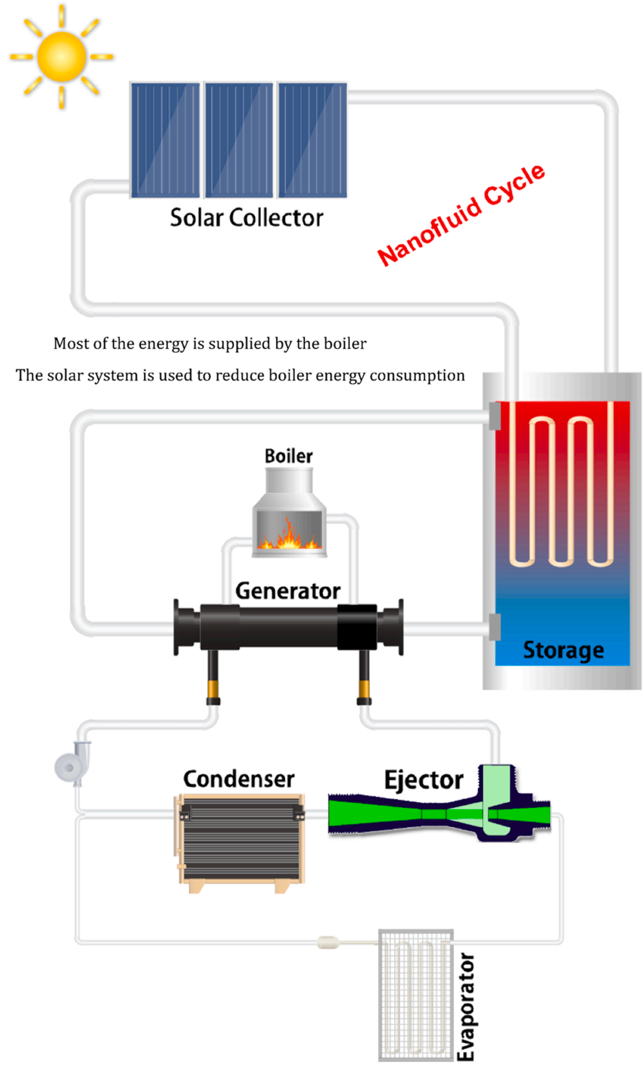

Fig. 1. The proposed HVAC system accomplished with solar energy.

where the value of φ for Taif is 21.3°, Sharorah is 17.48°, and Najran is 17.56°. To find I_d, the readers can use Eq. (2) [46]:

$$\frac{I_d}{I_H} = 1.0086 - 0.178\frac{G}{I_0}\frac{G}{I_0} < 0.24 \tag{2}$$

$$\frac{I_d}{I_H} = 0.96 + 0.1325\frac{G}{I_0} + 1.4183\left(\frac{G}{I_0}\right)^2 - 10.1862\left(\frac{G}{I_0}\right)^3 + 8.3733\left(\frac{G}{I_0}\right)^4 0.24 \le \frac{G}{I_0} \le 0.8$$

$$\frac{I_d}{I_H} = 1.0086 - 0.178\frac{G}{I_0}0.8 < \frac{G}{I_0}$$

$$I_{incidentoncollector} = \left[\frac{(\sin\varphi\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\gamma + \sin\delta(\sin\varphi - \cos\varphi\cos\gamma)}{\cos\varphi\cos\delta\cos\omega + \sin\delta\sin\varphi} + \frac{\rho}{2}\right]I_{beam} + I_{diffuse}\left(1 + \frac{\rho}{2}\right) \tag{1}$$

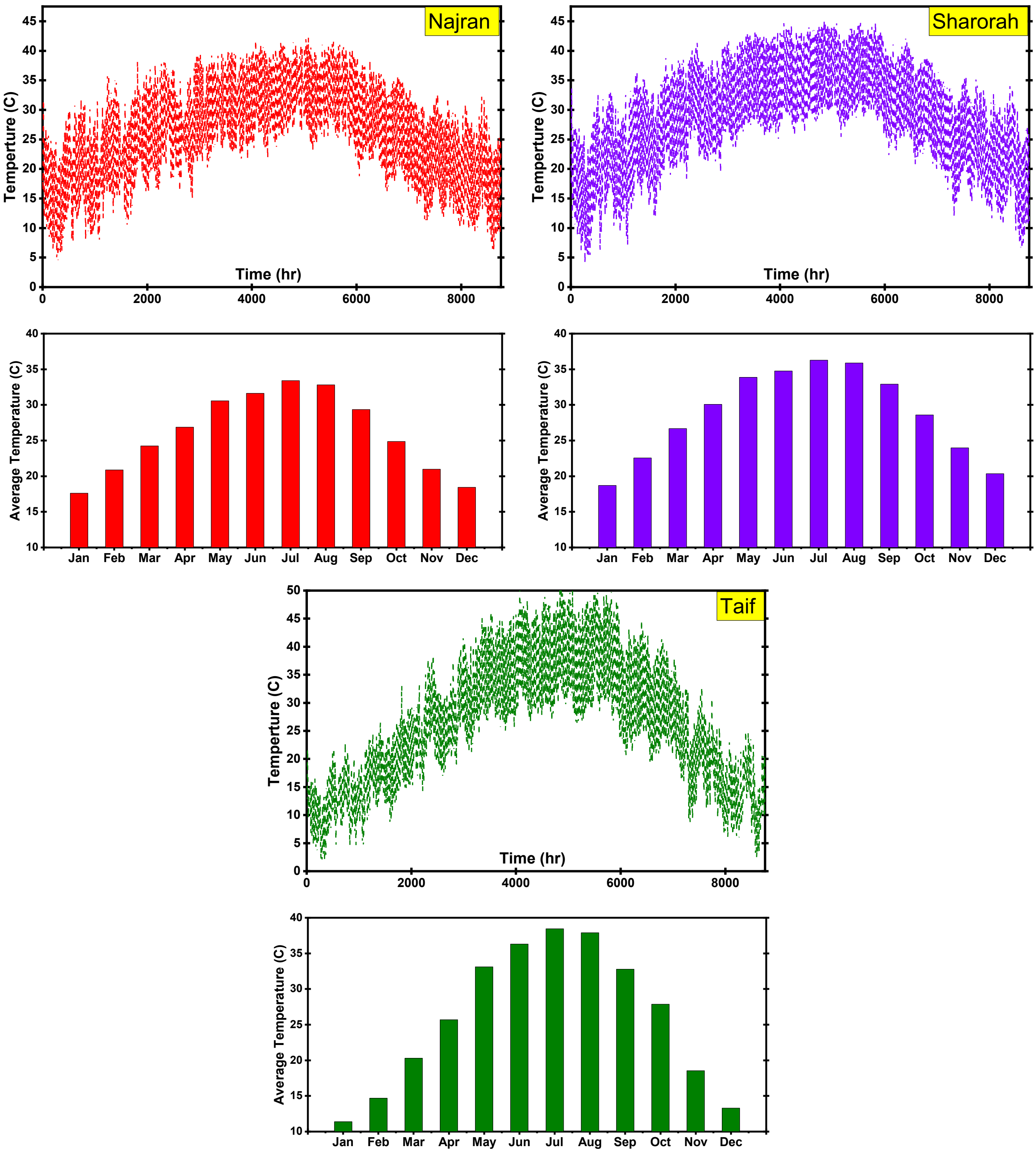

Fig. 2. Weather information for three climates in Saudi Arabia.

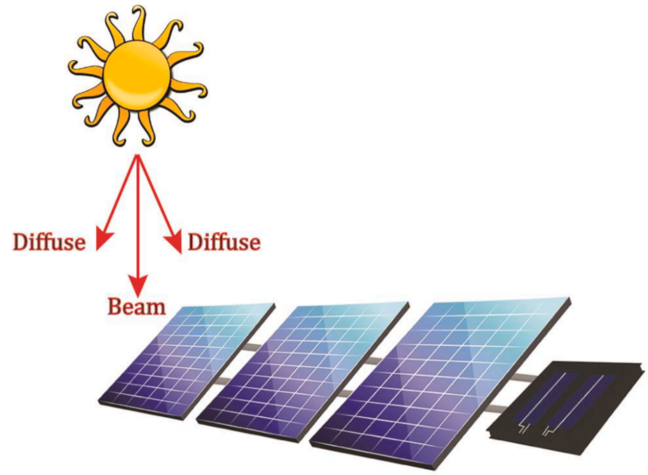

Fig. 3. Radiation on the collector surface.

where the variations in G is illustrated in Fig. 4.

It is necessary to find I_o (which is the radiation in the extraterrestrial region), the readers can use Eq. (3).

$$I_o = 18798\left[1 + 0.033\cos\left(\frac{2\pi n}{365}\right)\right]\left[\left((\sin\varphi)(\cos\delta) \times (\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180}(\sin\delta)(\sin\varphi)\right]\right. \quad (3)$$

The value of parameters of δ and ω are:

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + n)\right] \quad (4)$$

$$\omega = 15 \times \text{hour} - 180 \quad (5)$$

where ω is valid for hours within range of 6 a.m. and 6p.m.

Results

The main purpose of this study is to investigate the thermal behavior of solar collectors to identify energy saving. Solar collectors, like heat exchanger, trap solar energy and then turn it into thermal energy. The working fluid can be water, ethylene glycol or even nanofluid [47–51]. Various nanoparticles have been used in this field [52–55]. In this study, as in many studies [56–62], CuO nanoparticles (25 ppm, 50 ppm and 100 ppm) were used [63]. Thermal energy is forced to be stored in the water or any other working fluid, which, in turn, increases the fluid temperature so that over time, the temperature becomes high and higher and so that the temperature reaches its steady state [78–82]. Increasing temperature has two phenomena with it [83–85]. The higher temperature in the solar collector means that the amount of $(T - T_{amb})$ rises, and therefore the collector heat loss intensifies. On the other hand, many authors have pointed out that increasing the temperature improves the nanofluid conductivity relative to the base fluid [64]. Therefore, increasing the temperature has a positive effect and a negative effect. The positive effect is the increase of $k_{water+EG/CuO}$ compared to k_{CuO}, which itself causes more thermal storage, and its negative effect is the increase of heat loss to the external environment. Fig. 5 shows $\eta_{water+EG}$ and $\eta_{water+EG+CuO}$ in various dimensionless temperature $\left(\theta = \frac{T_i - T_{amb}}{I(t)}\right)$. For all samples, as θ increases, owing to heat loss intensification, heat loss augments and therefore $\eta_{water+EG}$ and $\eta_{water+EG+CuO}$. In other words, the lower value of heat loss, the higher $\eta_{water+EG}$ and $\eta_{water+EG+CuO}$.

For a more comprehensive study of the efficiency behavior and its sensitivity to nanofluid, we can refer to Figs. 6 and 7. The deep focus in Fig. 5 shows that there is a linear relationship between efficiency and θ :

$$\eta(t) = F_R(\alpha\tau) - F_R U_l \times \theta \quad (6)$$

In other words, it can be said that efficiency depends on two variables, $F_R(\alpha\tau)$ and $F_R U_l$ and its variations in Fig. 6 for $F_R(\alpha\tau)$ and for $F_R U_l$, Fig. 7 shows its changes.

Fig. 6, which shows the maximum efficiency (the $F_R(\alpha\tau)$ parameter), shows us that the maximum efficiency has a clear response to CuO nanoparticles, and this reaction is incidentally desirable. CuO nanoparticles have been able to enhance the heat absorption potential through the improvements they have made in diffusion and molecular collisions.

CuO nanoparticles intensify $F_R(\alpha\tau)$ by 19.15% at 25 ppm. By doubling CuO from 25 to 50 ppm, it is expected the parameter of $F_R(\alpha\tau)$ from 19.15% to 38.3%, while the rate of improvement is 24.25% as observed in Fig. 6. This trend is true even for the range of 50 ppm-100 ppm, and it can not be concluded that the more nanoparticles we add, the more efficiency we will have in the output.

Fig. 7 also shows the heat loss response to CuO nanoparticles. In the case of solar collectors, the only effective parameter is not thermal conductivity. But other parameters such as density and specific heat are also effective. Reference [63] states that the density is 1043.78 $\frac{kg}{m^3}$ for water + EG and 1044.55 $\frac{kg}{m^3}$ for nanofluid. The specific heat does not have a considerable sensitivity to CuO so that its value is 3674.29 $\frac{J}{kg.K}$ for water + EG and 3674.83 $\frac{J}{kg.K}$. On the other hand, higher density along with more heat capacity means more energy storage. Because for nanofluid, the values of density and specific heat remain constant, it can be concluded that in terms of these properties, nanoparticles did not have a significant effect.

CuO nanoparticles, due to higher thermal conductivity , have reduced thermal losses through the collectors. This phenomenon can be related to better molecular collision as well as better diffusion. Thermal losses for water + EG/CuO under the conditions of 25 ppm, 50 ppm and 100 ppm are lower by 10.26%, 8.7% and 5%, respectively.

In this study, the focus is on reducing EU in the HVAC section, and therefore two systems are used to provide heating and cooling, the ejector cooling system is used for cooling, and the boiler system is used for heating. For the cooling section, COP is defined as follow:

$$COP_{Cooling} = \frac{\overbrace{\text{Building Heat Gain}}^{BHG}}{Q_g + W_p} \quad (7)$$

But for heating system, it is defined as follow

$$\eta_{Heating} = \frac{\overbrace{\text{Building Heat Loss}}^{BHL}}{Q_{boiler}} \quad (8)$$

Their variations are shown in Fig. 8.

As generator temperature rises, COP increases which mean lower power is required in the generator section, which is recommended.

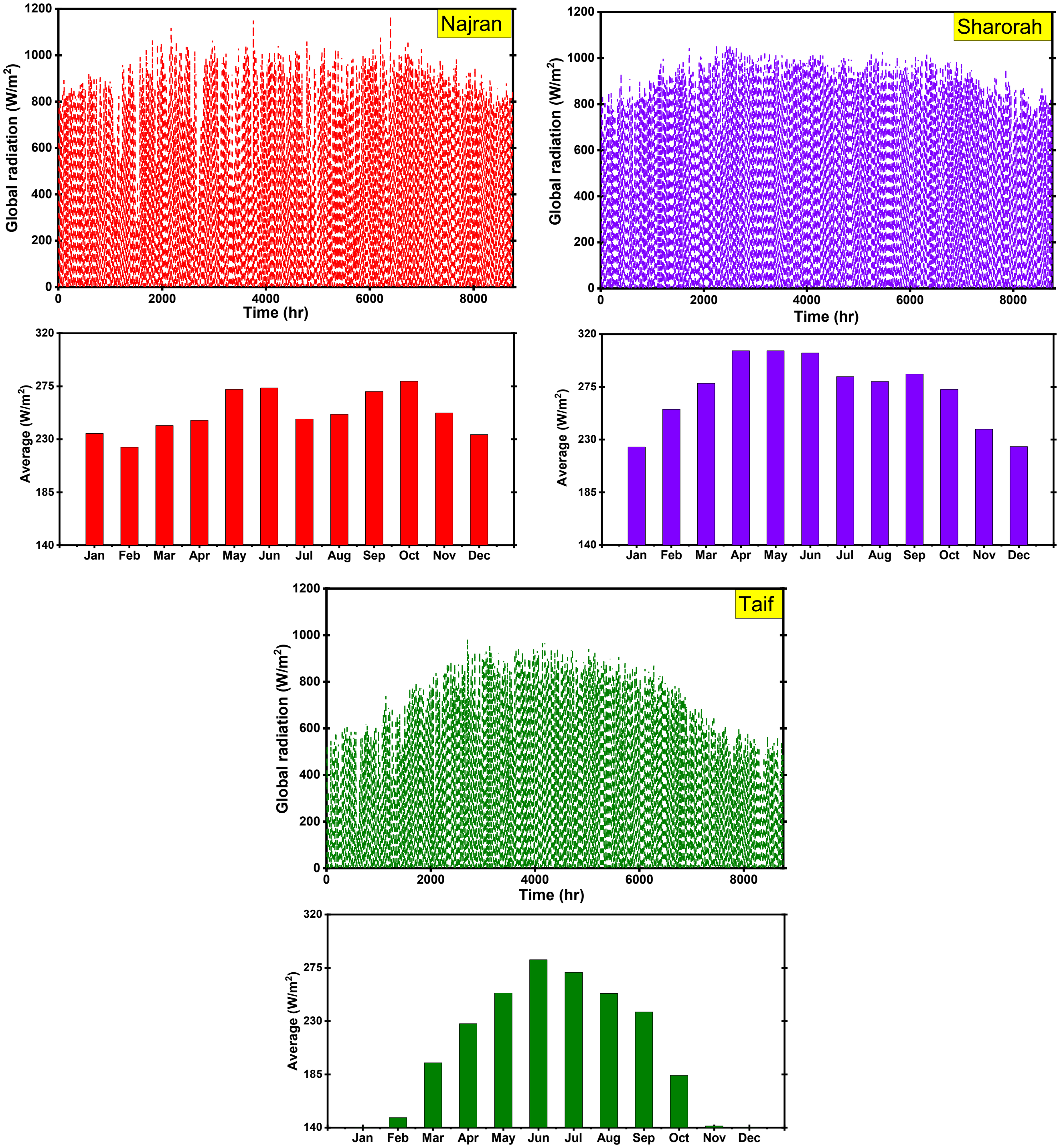

Fig. 4. The variations in global radiations (G) (hourly and monthly).

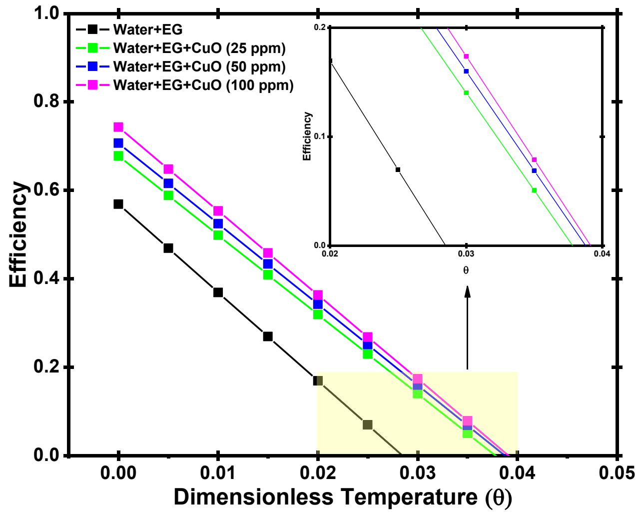

Fig. 5. Efficiency for water + EG and water + EG + CuO [63].

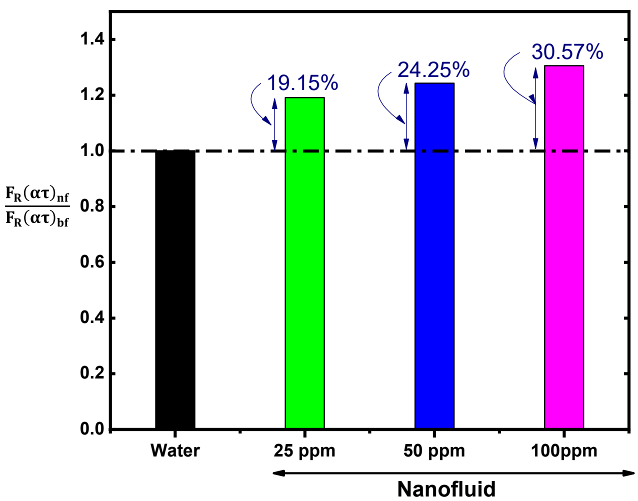

Fig. 6. Maximum efficiency for water + EG and water + EG + CuO.

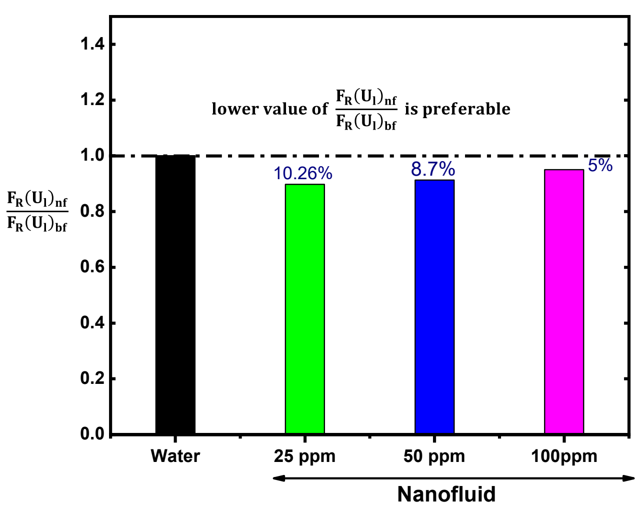

Fig. 7. Thermal losses for water + EG and water + EG + CuO.

Therefore, it is better to keep the generator temperature as high as possible. As the condenser temperature rises, COP reduces, and therefore it is recommended to keep the condenser temperature as low as possible. Finally, as the evaporator rises, COP rises and the designer should consider it, because, in HVAC design, the evaporator temperature is varied within 5–7 °C.

The variations in BHG and BHL are shown in Fig. 9.

Considering the efficiency of 0.8 for the boiler and considering COP variations in Fig. 8, annual BEU can be calculated using Eq. (9):

$$\text{AnnualBEU} = \frac{\text{BHL}}{\eta_{\text{Heating}}} + \frac{\text{BHG}}{\text{COP}_{\text{Cooling}}} \tag{9}$$

The results show that the annual BEU in the city of Najran is equal to 41,060 kWh while this figure for Sharorah and Taif is 52,449 and 37,376 kWh.

In this study, considering that a solar system has been used to assist the boiler, so the amount of reduction in EU can be obtained by considering Fig. 5. The results are reported in Fig. 10. It seems that the amount of energy saving in Sharorah is more than the other two regions. The total annual energy saving for Sharorah, Najran and Taif is 16440, 14,790 and 12,420 kWh, respectively.

Figs. 6 and 7 show that the addition of copper oxide nanoparticles improves SCE, and therefore it is expected that the energy-saving content of collectors using this additive will be higher. Fig. 11 reports the amount of energy saving for different regions under two conditions; base fluid (water + EG) and nanofluid.

Focusing on Fig. 11, it is found that:

1- Installing a solar system in Sharorah climate region has more positive effects than that of Taif and Najran.
2- For Sharorah, Najran and Taif, saving energy is 16440, 14,790 and 12,420 kWh, and the collectors were filled with water + EG.
3- Loading CuO at 25 ppm boosts the energy saving so that the calculations show that the energy-saving for Sharorah, Najran and Taif is 18730, 16,990 and 14,380 kWh, respectively.
4- Loading more CuO leads to more energy saving. At 100 ppm, CuO nanoparticles reduce BEU by 20430, 18,550 and 15,710 kWh.

Conclusion

Considering the high share of EU in residential and commercial buildings, the need to reduce EU in various building sectors can reduce air pollution and ultimately climate changes. In this study, focusing on reducing EU in HVAC system, a heating and cooling system was selected.

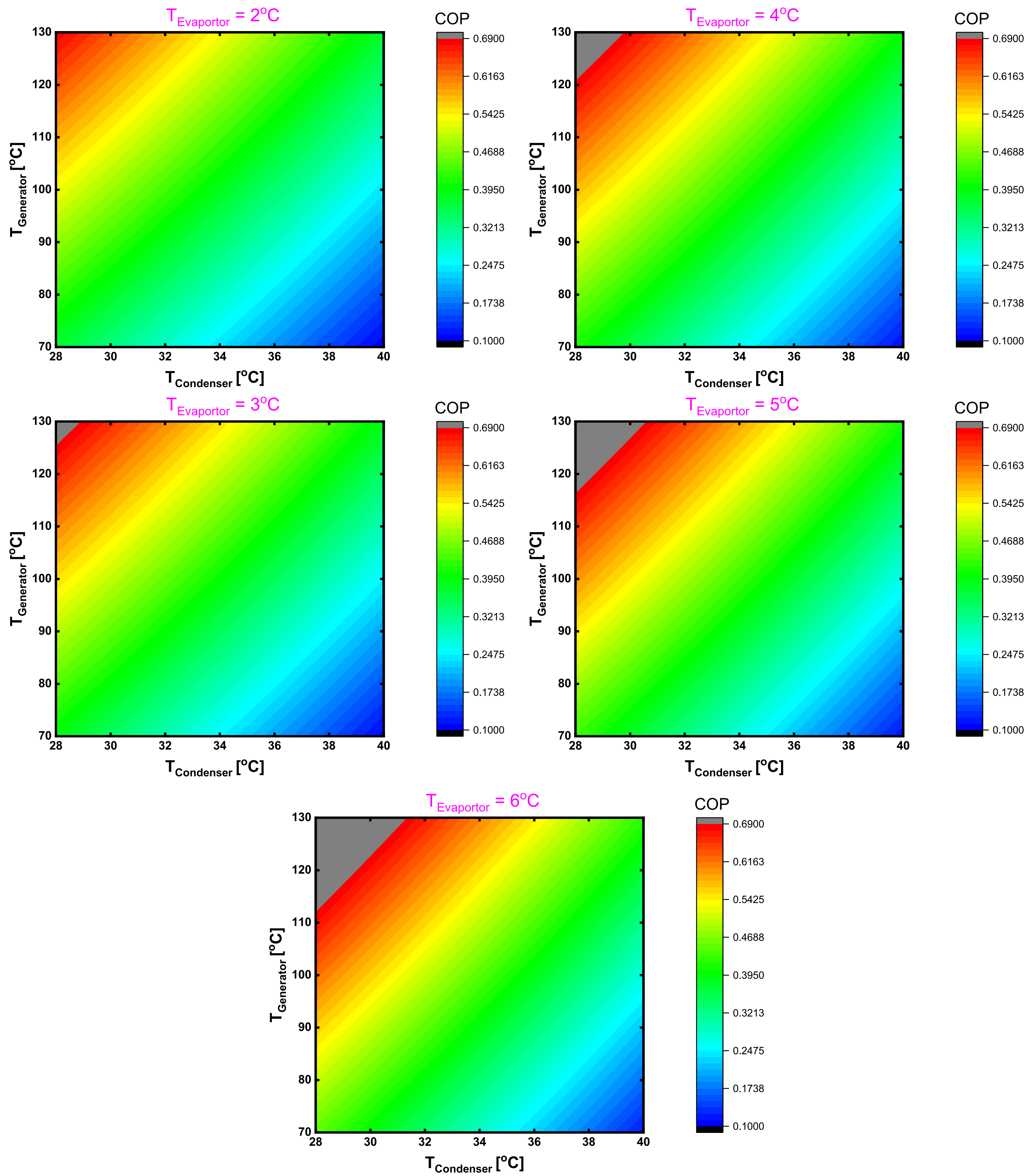

Fig. 8. COP variations and dependency to. T_C, T_e and T_g.

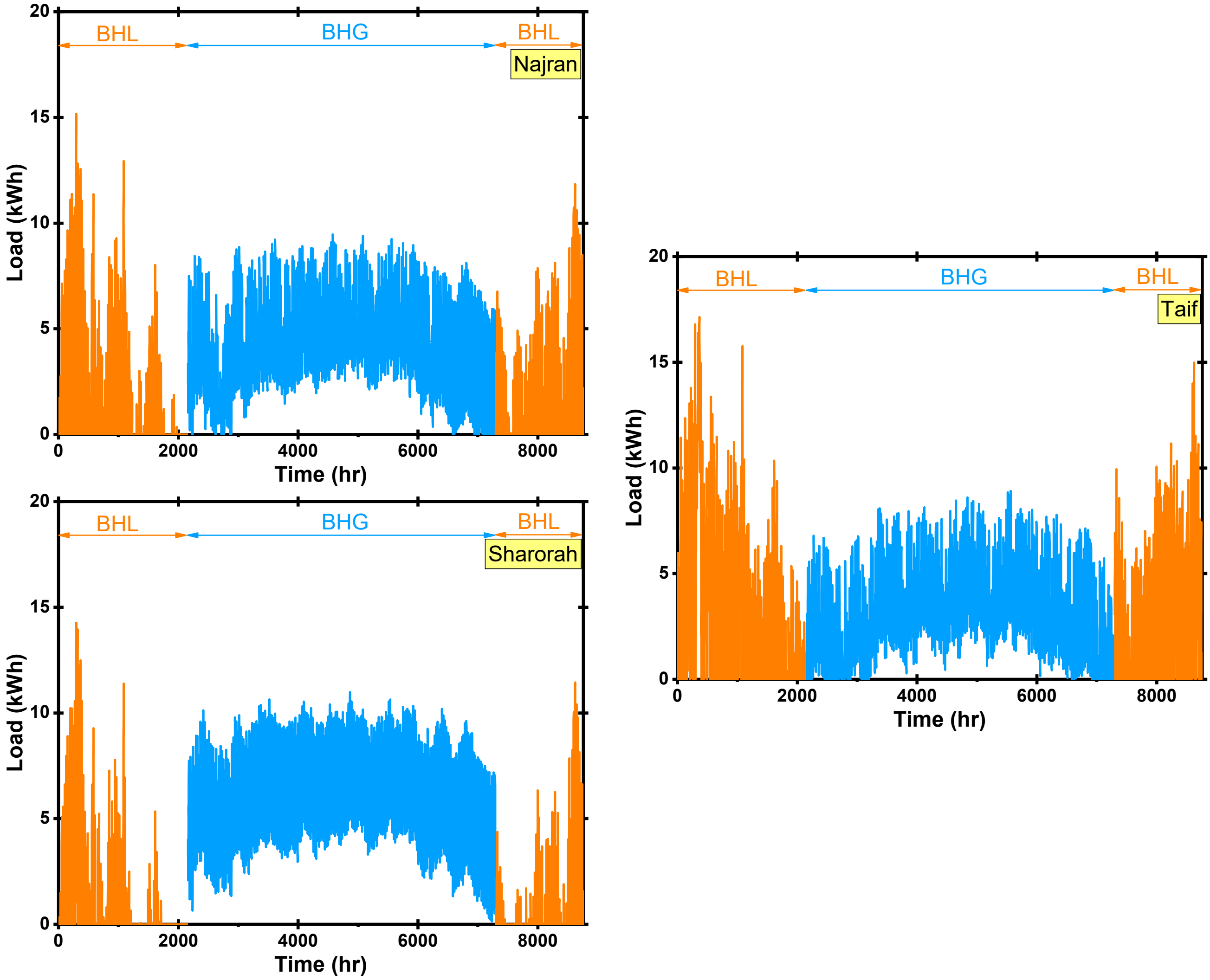

Fig. 9. The variations in BHL and BHG.

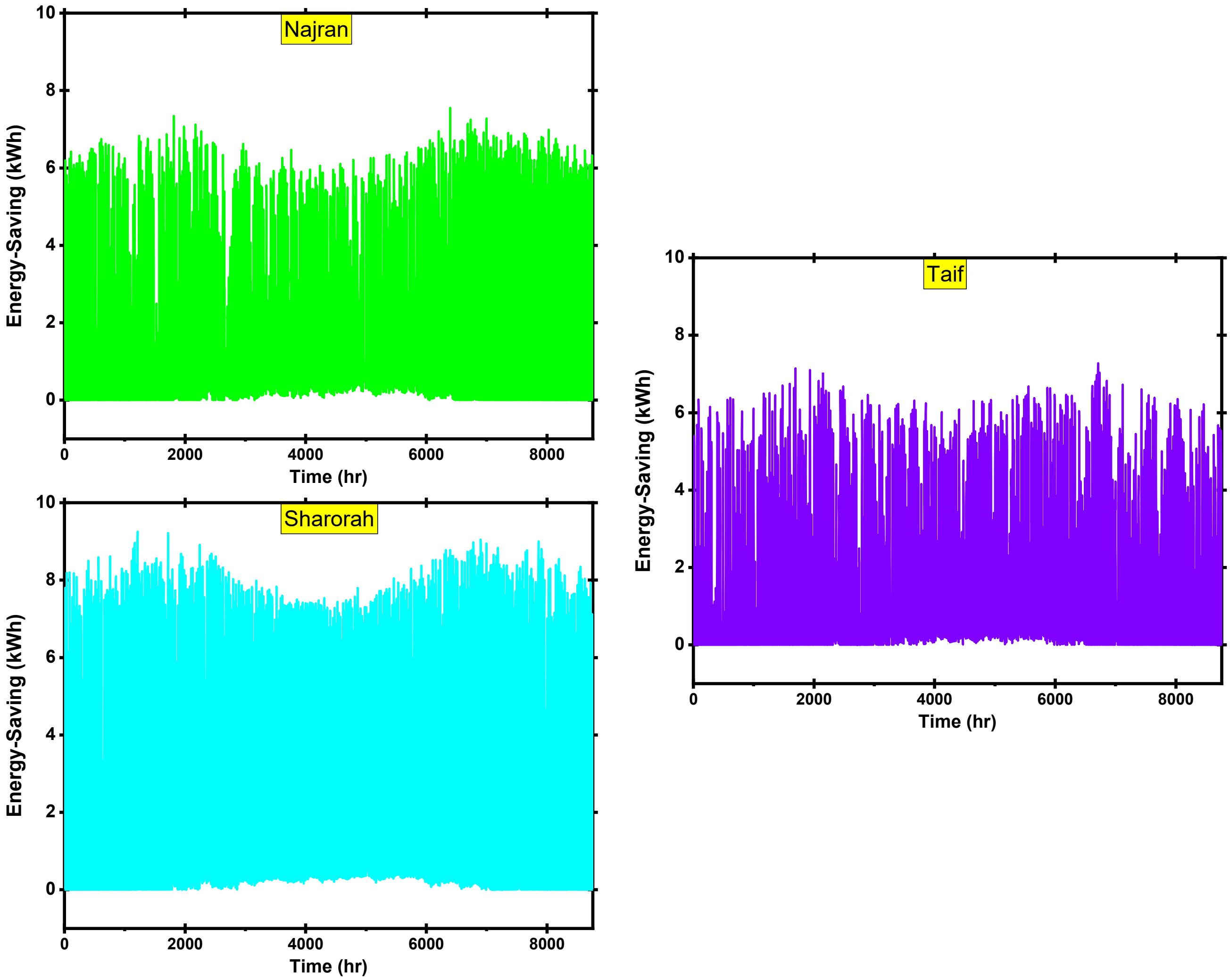

Fig. 10. Energy-saving through using water + EG filled solar collector at three climates.

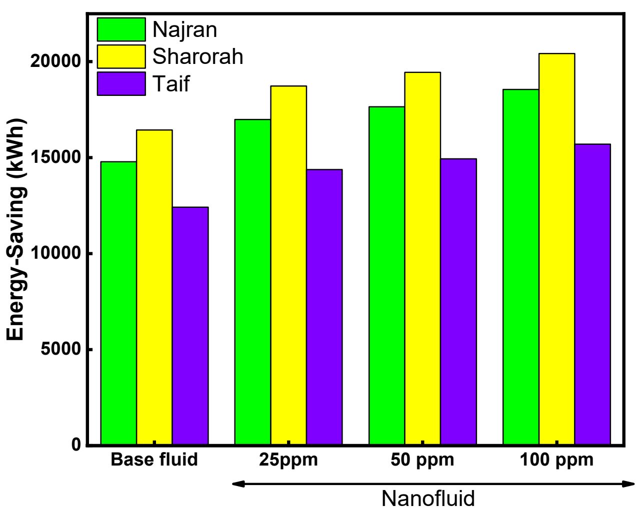

Fig. 11. Annual energy saving comparison in three climate.

In the cooling section, the boiler supplies the thermal energy and directing it to the generator to produce chilled water in the evaporator. For the heating system, the boiler system + fan coil was used. To drop EU in the boiler, a solar system was incorporated into HVAC system, and its usefulness was examined for three climate regions in Saudi Arabia

In Sharorah, adding a solar system led to more saving energy than that of Taif and Najran climate regions.

In Najran, using a solar system filled with water + EG reduced BEU by 14,790 kWh (36.2% reduction). Inserting CuO at 25 ppm boosted energy saving from 14,790 kWh to 16,990 kWh, which reduced BEU by 41.3%. At 50 ppm and 100 ppm, energy saving was 17,650 and 18550, which is equivalent to a 43% and 45.1% reduction in BEU.

In Sharorah, solar collectors were able to reduce BEU by 16,440 kWh (under the case of water + EG), while for nanofluid at 25 ppm, 50 ppm and 100 ppm, this figure was 18730, 19,440 and 20,430 kWh. In this climate, the solar system lowered BEU by 31% to 39%.

In Taif, using the solar system reduced BEU by 12,420 (for water + EG) and 15,710 (for nanofluid at 100 ppm). In this climate, solar collectors reduced EBU by 33% for water + EG and 42% for nanofluid at 100 ppm.

CRediT authorship contribution statement

Saeed Alqaed: Formal analysis, Writing – original draft. **Jawed Mustafa:** Writing – original draft. **Mohsen Sharifpur:** Conceptualization, Writing – review & editing. **Goshtasp Cheraghian:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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