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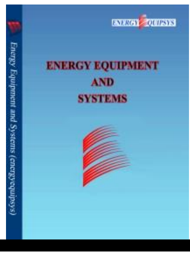

Energy and environmental performance of a grid-connected concentrating photovoltaic thermal system for residential buildings in Iran

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ABSTRACT

This paper evaluates the performance of a concentrating photo-voltaic thermal (CPVT) hybrid system for space heating, providing hot water, and grid-connected (GC) electricity generation in the city of Isfahan, Iran. The GC-CPVT system is a ground-mounted 5.63 kWp rated power system oriented in a north-south direction to achieve the maximum power output. The annual and monthly modeling of the system is performed by Polysun® simulation software. The system specifications are described and the heating and electrical energy demand of the building are determined. The GC-CPVT performance simulation is then conducted based on the meteorological data of the location. The monthly simulation results of the GC-CPVT system in the studied location show that the yield factor varies from 138.8 to 183 kWh/kWp, the reference yield from 170.3 to 253.5 kWh/kWp, and the performance ratio from 70.3 to 82.2%. The maximum annual AC electricity generated is 10752 kWh. Furthermore, the CPVT system generates a considerable amount of heat. The annual solar fraction values for covering domestic hot water and space heating are achieved 78.3% and 35.3%, respectively. The monthly solar fraction covered by the CPVT system also varies from 32 to 100%. The environmental performance of the GC-CPVT system indicates that the contribution of such a system to CO_2 emission reductions exceeds 8 tons of CO_2 per year.

Keywords: Concentrating Photovoltaic Thermal; Grid-Connected; Residential Heat; Performance Simulation; CO_2 Saving.

1. Introduction

Fossil fuels are considered as an energy resource in many countries not only causes environmental issues but also leads to an imminent shortage of non-renewable energy sources in the future [1]. Nevertheless, the percentage of fossil fuel consumption in the world was reported around 80% in 2015 [2]. Among all energy-consuming sectors, the building sector consumes a significant amount of energy. Energy consumption in the residential sector accounts for 25% of the global energy consumption and 17% of the CO_2 emission worldwide [3]. In Iran, energy consumption in residential buildings including electricity and heat is mainly based on fossil fuels. In 2015, 29.6% of total consumed energy was used in the residential sector. Moreover, 86.7% of total energy consumption in the residential sector was supplied by fossil fuels including natural gas and oil products [4]. Fortunately, serious attention globally has been

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focused on renewable and clean technologies to substitute conventional energy sources [5].

One of the plentiful energy resources on the earth is solar energy. In recent years, solar energy conversion technologies have been received increased attention [6]. Solar thermal devices and Photovoltaic (PV) convert the solar energy into heat and electricity in solar thermal collectors and PV cells, respectively. An emerging technology to simultaneously produce electricity and heat for residential buildings is the hybrid photovoltaic thermal (PVT) system. In these systems, the heat generated in PV cells can be employed for space heating or domestic hot water (DHW) provision [7]. Compared to solar thermal collectors and PV panels, PVT systems have not yet been commercialized; however, interest in these systems has increased in recent years due to lower PV module prices [8].

The concentrating photovoltaic thermal (CPVT) system is a novel combination of concentrating photovoltaic (CPV) and PVT to generate superior heat and power. In CPVs, the solar insolation is focused on the PV panels to produce more electricity than a normal flat PV cell [9]. CPVT systems also use this technology. Furthermore, the thermal energy produced in the PV cells due to the concentration of sunlight is used for processes that require heat [10]. The main issues of PVT systems, i.e. high investment for generating desired electricity and low output temperature, have been solved in CPVT systems. CPVT systems possess fewer PV cells with higher combined heat and power efficiency [11].

In recent years, various configurations of CPVT systems have been widely studied. Coventry [12] investigated the performance of a CPVT collector. Measured results showed the combined efficiency of 69% for the CPVT system. Kribus et al. [13] presented a CPVT system producing electricity and heat for a nearby consumer. They investigated both of thermal and electrical performance costs of the system and produced energy. The efficiency of the system was almost 80%. Also, the payback time of 10 years was achieved at the electricity cost of 5 ¢kWh^{-1}. Mittelman et al. [14] studied a CPVT system operated at elevated temperatures. The produced thermal energy was used for absorption cooling. Results showed that the combined solar cooling and power production are comparable with regular alternatives. Thermal, electrical, and cooling efficiency of the system were nearly 60%, 20% and 40%, respectively. The same authors proposed a CPVT system for water desalination [15]. They performed simulations to compute the annual production of electricity and water. A total efficiency of 80% was obtained for the hybrid system. Li et al. [16] experimentally investigated electrical and thermal performance of a trough CPVT based on different PV cells. Experimental results of concentrating silicon cell array showed that the thermal and electrical efficiency of the CPVT was 42.4% and 7.51%, respectively. Bernardo et al. [17] proposed a methodology to characterize and simulate a CPVT hybrid system installed in Lund Technical University, Sweden. Their simulation was validated by experimental outputs of the system. An electrical efficiency of 6.4% was obtained. Al-Alili et al. [18] utilized a CPVT system for simultaneous generation of heat and electricity applied in an air conditioning system. A TRNSYS simulation was employed for Abu Dhabi condition. The simulation results showed that the annual overall COP of the hybrid system was found to be than that of the other solar air conditioners. The maximum average COP of 60% was achieved. CPVT systems with Fresnel lenses and parabolic mirrors concentrators were studied from the economic and energy attitude in Italy by Renno and Petito [19]. Results of simulation for southern Italy indicated that the configuration with mirrors (81 mm^2 cell area and two modules with 90 cells) produced energy which is sufficient for electric and cooling demands, while an auxiliary heating system was essential for some months of the year. The fluid temperature of 90°C was obtained. Also, the discount payback year was 8 years. Calise et al. [20] performed a dynamic simulation of CPVT system integrated in solar heating and cooling. The system provided space heating and cooling, electricity and DHW for a sample building. The produced electricity was consumed by building and the excess was sold to the public grid. Thermal energy by the CPVT was used in an absorption chiller. Time basis Energetic and economic performances were also evaluated. They showed that for a 500 m^2 collector area the solar fraction of 75% can be obtained. In comparison with a system with a flat plate collector, the primary energy saving was 84.4% versus 70.2%. Karathanassis et al [21] designed and experimentally evaluated a parabolic-trough CPVT system. Results showed that the electrical and thermal efficiency of the system was almost 6% and 44%, respectively. Moreno et al. [22] designed a CPVT for use on the south-facing windows of buildings. In their design, a PV cell was immersed in deionized water. A polymethyl methacrylate concentrator linearly concentrated sunlight on it. Deionized water cooled the PV cell. The energy performance of the building integrated with this system was simulated for three European cities. The results showed that this system could provide up to 74% of the thermal energy required for DHW and 68.7% of the energy required for space heating. Moaleman et al. [23] employed a CPVT system with Fresnel linear collector to generate electricity, heating, and cooling simultaneously in Tehran. The performance of this tri-generation system was simulated by TRNSYS software. The overall efficiency of this system was 71% with an annual electricity generation efficiency of 12.8%. Also, its heating and cooling efficiencies were 58.01% and 34%, respectively. Anand and Murugavelh [24] modeled a hybrid CPVT system used for power generation, desalination and cooling. The system was simulated for the geographical conditions of Vellore, India and two days of the year. The results of the daily analysis showed that the output temperature of saline from the CPVT collector was in the range of 34.47°C - 68.45°C and the generated electricity was in the range of 0.21 kW - 1.36 kW. The highest energy utilization factor was 0.31. Annual power generation, cooling and desalination capacity were 3.46 MWh, 0.788 MWh and 4.2 m^3, respectively. Alayi et al. [25] a hybrid CPVT system with a parabolic trough collector and PCM storage tank was simulated to generate electricity, heating and cooling a building in Tehran**.** The average collector outlet temperature was 88°C. It was shown that the lowest and highest monthly thermal production is 16.4 kW and 51.31 kW. Also, the maximum and minimum electrical power generation by CPVT system were 18.81 kW and 6.01 kW in June and January, respectively. Hussain and Kim [26] proposed a focused CPVT system for heating a building located in Chuncheon city in South Korea. Results illustrated the highest electrical and thermal efficiencies of the collector were 18.5% and 65.2%, respectively. Assuming that the useful life of the CPVT system is 25 years, the discounted payback period for natural gas will be 12 years.

The energy and environmental performance of CPVT systems to produce simultaneous heat and electricity for residential buildings have been received insufficient attention in recent years. The overall purpose of this paper is to assess the thermal, electrical, and environmental performance of a grid-connected CPVT (GC-CPVT) system installed in city of Isfahan, Iran. To the best of our knowledge, such a performance study on the simultaneous production of electricity and thermal energy by CPVT systems has not been conducted so far. In this paper, a 5.63 kWp rated power CPVT system was employed to provide space heating, DHW and GC electricity. Using Polysun® simulation software, monthly and annual grid-connected PV indices were calculated to estimate the performance of PV part of GC-CPVT. The solar fraction was also utilized to assess the thermal performance. Moreover, the saving of CO_2 emission by using GC-CPVT system was investigated.

Nomenclature

DHI	Diffuse Horizontal Irradiance, kWh/m^2
DHW	Domestic Hot Water
DNI	Direct Normal Irradiance, kWh/m^2
E_{AC}	AC energy output of the system, kWh
$E_{sol\ PV}$	Solar radiation on to the module area, kWh
GC-CPVT	Grid-Connected Concentrating Photo-Voltaic Thermal
GHI	Global Horizontal Irradiance, kWh/m^2
H_R	Array reference irradiance (= 1 kW/m^2)
H_t	Total irradiance onto module area, kWh/m^2
PR	Performance Ratio (%)

$P_{r,PV}$	Maximum rated power of the panels, kWp
PV	Photo-Voltaic
Q_{aux}	Energy generated by the auxiliary system, kWh
Q_{sol}	Energy supplied by collectors to the system, kWh
SF	Solar Fraction (%)
STC	Standard Test Condition
T	Temperature, ºC
Y_F	Final yield (kWh/kWp)
Y_R	Reference yield (kWh/kWp)

2. Solar energy in Iran

Iran is a Middle Eastern country that is bounded on the north by the Caspian Sea and by the Persian Gulf and the Oman Sea in the south. Its other borders are shared with Armenia, Azerbaijan, Turkey, Iraq, Pakistan, Afghanistan, and Turkmenistan. Iran's climate is warm and dry, affected by subtropical aridity of the Arabian Desert and subtropical humidity of the eastern Mediterranean area [27]. In most areas, summers are long, hot, dry, and winters are short and cold.

Iran has considerable diversity in renewable energy sources mainly including wind, solar, biomass, and geothermal. A considerable focus on renewable energies has been recently done, although having rich oil and gas resources, low prices for fossil fuels, and lack of awareness of the benefits of renewable energies have slowed down the growth of using these resources [28]. As of March 2020, the total installed capacity of renewable energy plants and energy efficiency in Iran was 885 MW. Moreover, another 345MW of renewable power plants is currently under construction. Also, the contribution of renewable energies in power generation is solar energy 44%, wind energy 34%, biomass energy 1%, hydropower 12%, and waste heat recovery 2%. Since 2016, the Iranian Ministry of Energy has guaranteed the purchase of electricity from clean and renewable sources [29].

Solar energy in Iran is remarkable because of more than 300 clear sky sunny days annually [30]. The average annual solar irradiance in Iran is estimated to be 4.5-5.5 kwh/m^2.day. The southern shores of the Caspian Sea have the lowest amount of irradiance (about 2.8kWh/m^2.day) due to cloudiness, rainfall, and high humidity, while the central and southern regions of Iran have the highest solar irradiance (Fig. 1 (a)). Figure 1 (b) shows Iran's GIS map for areas with the highest potential for PV power plants. The efficiency of PV panels decreases with increasing temperature, high winds, and specks of dust, so the climate of a region has a major impact on PV electricity generation [31, 32].

Using solar energy to generate heat for residential buildings is one of the advantages of solar energy in Iran [33]. Due to the average high temperature and good solar radiation in southern parts of Iran, solar water heaters can be replaced by existing electric water heaters. In Tehran, the capital of Iran, if only 25% of the population uses solar water heating systems, about 1,310,000 MWh/yr will save on fossil fuel consumption, equivalent to a reduction of 503,078 tons of CO_2 emissions [34]. In Iran, solar collectors (flat-plate or evacuated tubes) are used to producing solar hot water. To promote solar water heater use in Iran, the government has been building solar baths in deprived areas of Iran, installing solar water heaters for villagers and tribes to prevent deforestation, and installing water heaters to provide hot water for student dormitories, public toilets, and so on.

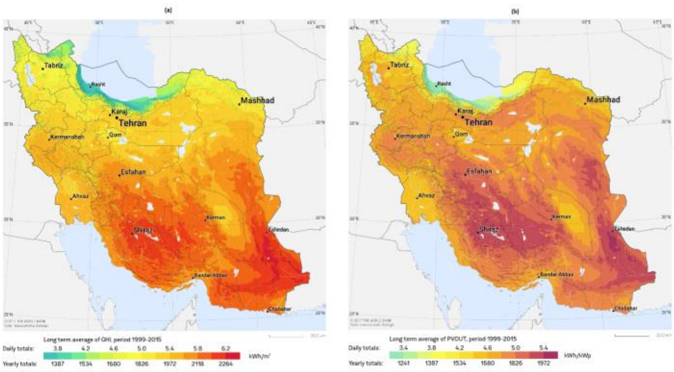

Fig. 1. (a) Global horizontal irradiation in Iran (kWh/m^2.day) (b) PV power potential map of Iran [31]

3. Methodology

3.1. Local meteorological data

In this study, the city of Isfahan where located in the central area of Iran is selected with the aim of studying the performance of GC-CPVT system. It possesses a moderate and dry climate. Average annual weather data for the studied location is listed in Table 1.

According to the average annual outdoor temperature of 16.3°C and heating degree day of 1952, heating load is dominant in terms of energy consumption in the location [35]. Monthly average meteorological data including the outdoor temperature, wind speed and air relative humidity of the studied location is presented in Table 2. These parameters, along with solar radiation and dust deposition, are important in the performance study of solar cells [36]. It can be seen from Table 2 that the minimum and maximum temperatures of Isfahan occur in January and July, respectively.

The hourly outdoor temperatures of the studied location are shown in Fig. 2. The maximum outdoor temperature is 40.9°C which occurs in 21th of July at 15:00. The coldest day of the year is January, 12 at 23:00 that the minimum temperature is -11.4°C.

Table 1. Average annual weather data for studied location

Parameter	Quantity	Unit
Location	Isfahan	-
Latitude	32.62	º
Longitude	51.67	º
Altitude	1550	m
Average annual relative humidity	35.4	%
Average annual outdoor temperature	16.3	°C
Average annual wind speed	2.8	m/s
Heating degree day	1952	-

Table 2. Monthly average meteorological data

	Outdoor temperature (°C)	Wind speed (m/s)	Air humidity (%)
January	1.5	2.2	56.1
February	5.6	3.0	41.4
March	11.2	3.4	31.7
April	16.1	3.6	33.5
May	21.9	3.6	26.8
June	26.8	3.2	22.6
July	30.0	2.9	22.5
August	28.2	2.7	22.8
September	23.3	2.5	25.0
October	17.3	2.5	33.4
November	8.8	2.1	49.4
December	3.7	2.0	59.9

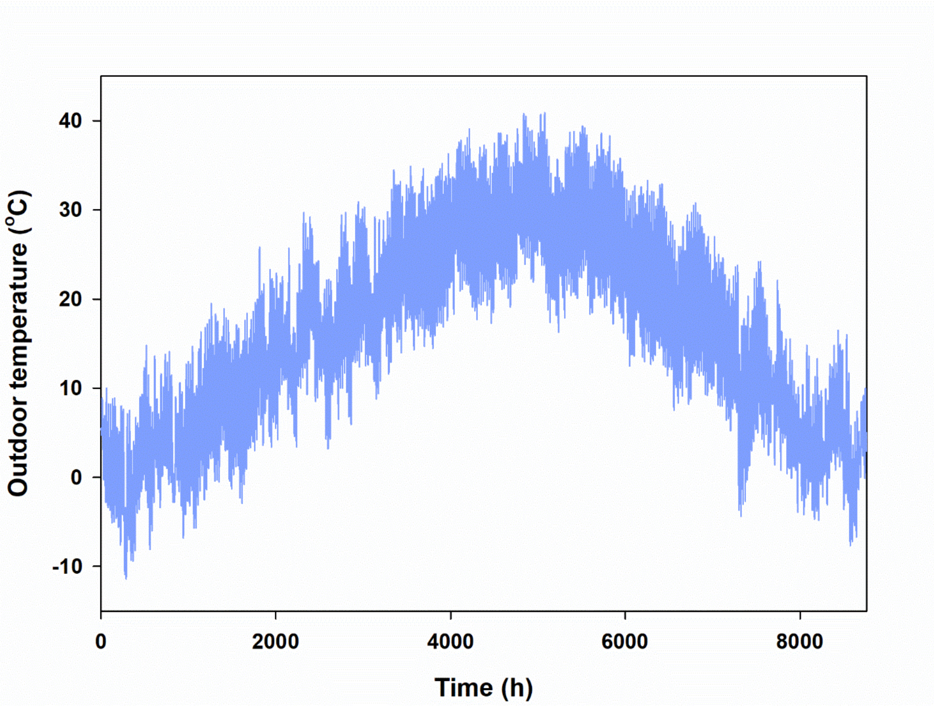

Fig. 2. Hourly outdoor temperature of the studied location

Figure 3 shows the GHI (global horizontal irradiance), DNI (direct normal irradiance) and DHI (diffuse horizontal irradiance) in the city of Isfahan in different months of the year. The highest amount of GHI is 239 kWh/m^2 in July and the lowest amount is 94.4 kWh/m^2 in December. Also, DNI has the maximum value in September and the minimum value in December which are 275 kWh/m^2 and 152 kWh/m^2, respectively.

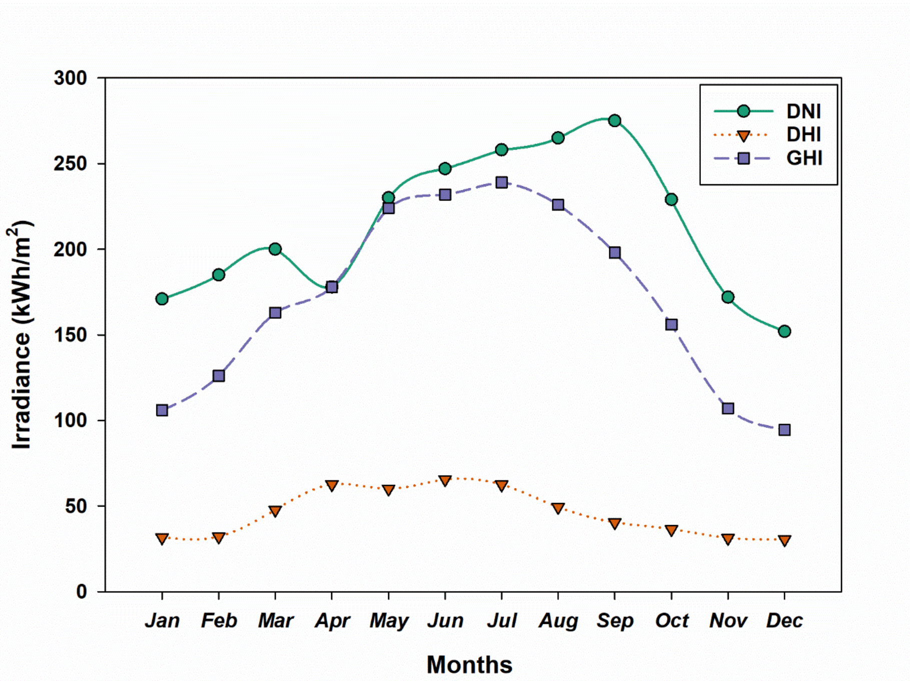

Fig. 3. Monthly average irradiance

As previously mentioned, the total average daily solar radiation in Iran is equal to 4.5-5.5 kWh/m^2.day. Isfahan almost has total annual radiation of 2050 kWh/m^2 or daily average of 5.6 kWh/m^2.day which is more than average.

Figure 4 illustrates the global radiation during the year as well as the diffuse radiation for the city of Isfahan. The highest average hourly global radiation value (i.e. 1156 W/m^2) is achieved in August, 4 at 12:00. Due to the lack of cloudy and rainy days, the diffuse radiation is dramatically low during the year.

3.2. System description and performance simulation

The performance assessment of GC-CPVT systems for the provision of space heating, DHW, and grid-connected electricity has been investigated. The modeling of the GC-CPVT system is carried out by Polysun® software (version 11.0). This software has been utilized for the simulation and design of solar energy systems. In this paper, the system specifications are firstly described and the energy demand (electricity and thermal) of the building are determined. Then, the design parameters are input to the software, and system performance simulations are conducted based on the meteorological data of the location (Isfahan, Iran).

The GC-CPVT system consists of three SunBase 1.0 ground-mounted CPVT collectors of 1878 Wp each, manufactured by Cogenra Solar Inc. A sun-tracking system are employed to gather the direct solar radiation. The CPVT collectors are oriented in north-south direction and track the sun along the axis in the east-west to maximize the received solar radiation [23]. Figure 5 shows the schematic diagram of the GC-CPVT system simulated in Polysun® and a Cogenra's CPVT collector.

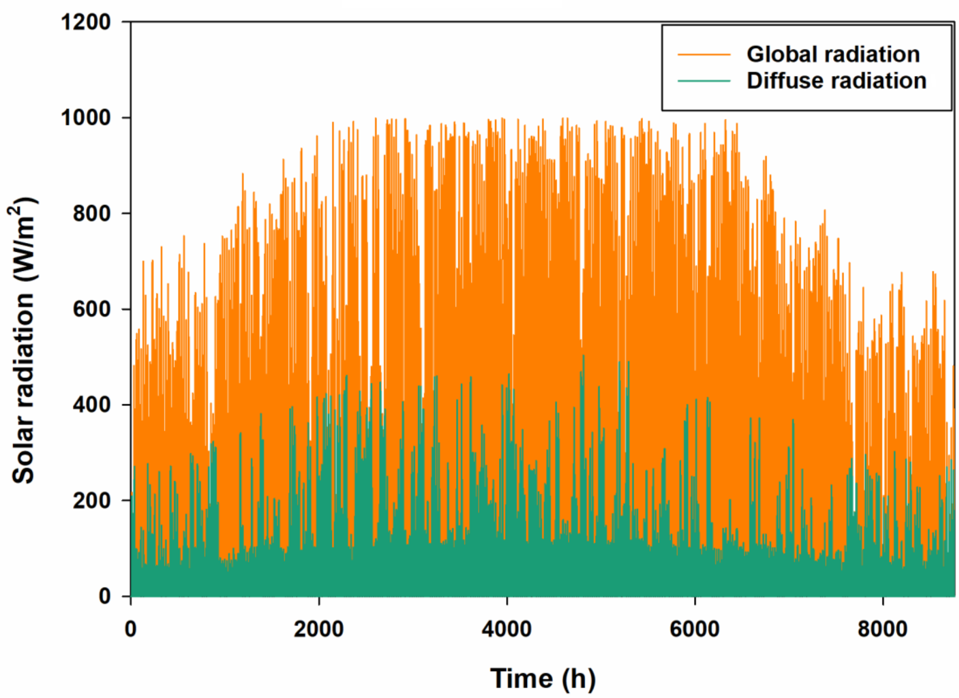

Fig. 4. Global and diffuse radiation of Isfahan

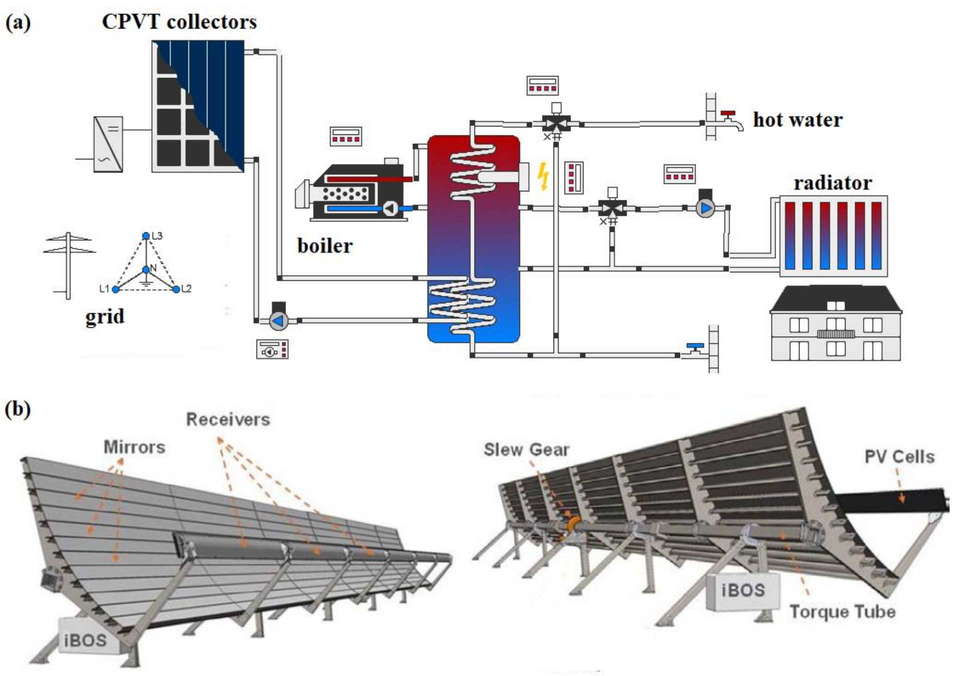

Fig. 5. (a) The GC-CPVT system simulated in Polysun® (b) Cogenra's CPVT collector [37]

The hybrid CPVT system consists of a number of ground-mounted arrays that independently track the sun. There are a series of flat mirrors on each array that focus sunlight on the polycrystalline module and generate electricity. There are a number of ducts on each panel through which a mixture of water and glycol flows and cools the PV cells [37]. The water storage tank has 3000 L capacity. There are heat exchangers in the water storage tank for extracting heat from the solar loop, pre-heating and heating tap water. A 25 kW auxiliary boiler and space heating loop are directly connected to the storage tank.

The thermal and electrical specifications of CPVT collectors are given in Table 3.

Table 3. CPVT collector data

parameter	value	unit
Module type	Polycrystalline	-
Aperture area	16.38	m^2
Absorber area	1.59	m^2
Module Efficiency STC*	11.01	%
Nominal power STC	1878	W
Temperature coefficient	-0.423	(%/K)
Output voltage MPP-STC	132	V
Output current MPP-STC	14.2	A
Open circuit voltage	174.2	V
Short circuit current	15.8	A
Test flowrate	363.6	L/min
Fluid volume	4.4	L
Diffuse irradiation fraction	0.157	-
Effective thermal capacity	66.388	kJ/kg
Max. temperature	100	°C
Max. pressure	3	bar

* STC: irradiance of 1000W/m^2 and cell temperature of 25°C

The building is located southward with dimensions of 12×9×2.4 (length× width× floor height). It has two floor with radiating heat system. The nominal inlet temperature to the radiators is 60°C and the nominal return temperature is 50°C. It is a normal building in terms of energy consumption. The main characteristics of the building are listed in Table 4.

Table 4. Main characteristics of the multi-family building

Parameter	value	unit
Heated living area	216	m^2
Heating set point temperature (day)	23	℃
Heating set point temperature (night)	16	℃
U-value of the building	0.5	$W/m^2.K$
Specific heating energy demand	150	kWh/m^2
Window-to-wall area ratio (South)	25	%
Window-to-wall area ratio (North)	13	%
Window-to-wall area ratio (East)	25	%
Window-to-wall area ratio (West)	6	%
Air change/infiltration	0.3/0.6	hr^{-1}
Heat capacity of the building	500	$kJ/m^2.K$

In the abovementioned building, two four-person families live who are considered high consumption in terms of DHW consumption pattern. The highest consumption of DHW for a high-consumption family is 70 L of hot water with a temperature of 45℃ [38]. Due to the fact that the standard DHW temperature in Iran is 60℃, the amount of DHW consumption with a temperature of 60℃ is converted from the following equation [39]:

$$V_{60} = (45 - T_C)/(60 - T_C) \times V_{45} \quad (1)$$

Considering the lowest monthly outdoor temperature, $T_C \sim 1.5$℃ can be obtained and as a result, the approximate amount of DHW consumption with a temperature of 60℃ is equal to 400 L.

The energy produced by GC-PV modules may decrease by a variety of losses including soiling, degradation, cables, mismatching and so on [40]. These factors are listed in Table 5. The inverter with IG Plus 55 V-2 model made by Fronius International GmbH is used for converting DC-produced electricity to AC electricity. The parameters of the inverter is also listed in Table 5.

Table 5. GC-PV module parameters

parameter	value	unit
PV panels losses		
Soiling	2	%
degradation	0.5	%
Cable loss	2	%
mismatching	4	%
inverter		
model	IG Plus 55 V-2	-
DC maximum power at cos φ=1	5260	W
Max. input current	22.9	A
Max. short circuit current	34.4	A
MPP voltage range	230-500	V
Max. output nominal	5000	W
Max. output voltage	270	V
Max. output current	10.9	A
Max. efficiency	95.7	%

Energy and environmental performance of the GC-CPVT system are evaluated using solar thermal energy to the system (Q_{sol}), solar fraction (SF) AC electrical energy output (E_{AC}), final yield (Y_F), reference yield (Y_R), performance ratio (PR), and CO_2 emission reduction:

$$SF = \frac{Q_{sol}}{Q_{sol} + Q_{aux}} \times 100 \tag{2}$$

$$Y_R = \frac{H_T}{H_R} \left[\frac{kWh/m^2}{kW/m^2}\right] \tag{3}$$

$$Y_F = \frac{E_{AC}}{P_{r,PV}} \left[\frac{kWh}{kWp}\right] \tag{4}$$

$$PR = \frac{Y_F}{Y_R} \times 100 \tag{5}$$

4. Results and discussion

4.1. Energy performance of GC-CPVT system

As mentioned before, the efficiency of PV cell can be influenced by its temperature. PV panels perform better at low temperatures than at high temperatures. As the power generated by PV cells at a lower temperature is more than the high temperature. A panel heats up when it is exposed to sunlight. In hybrid systems, some of this heat is transferred to the heat transfer fluid, and the panel temperature drops. Simulated hourly temperature of PV receiver is shown in Fig. 6. As seen, the maximum temperature of PV receiver during operation is 95.7°C which occurs at 11:00 A.M. on October, 10. The average annual temperature of PV cells can be achieved 64.1°C. The cell temperature in CPVT systems is a function of air temperature, direct normal irradiance, hours of the day and concentration factor [41].

Figure 7 illustrates the monthly average temperature of CPVT collector during operation. The highest operating temperature can be achieved in July and August which is 69.5°C, while the lowest operating temperature occurs in January and is equal to 54.4°C. The CPVT optimum operating temperature range for electricity and useful heat production was reported 75-125°C [42]. Due to higher air temperature in summer in addition to lower hot water consumption, the monthly cell average operating temperature is higher during summer. Moreover, according to Fig. 3, the DNI has the maximum value in July to September.

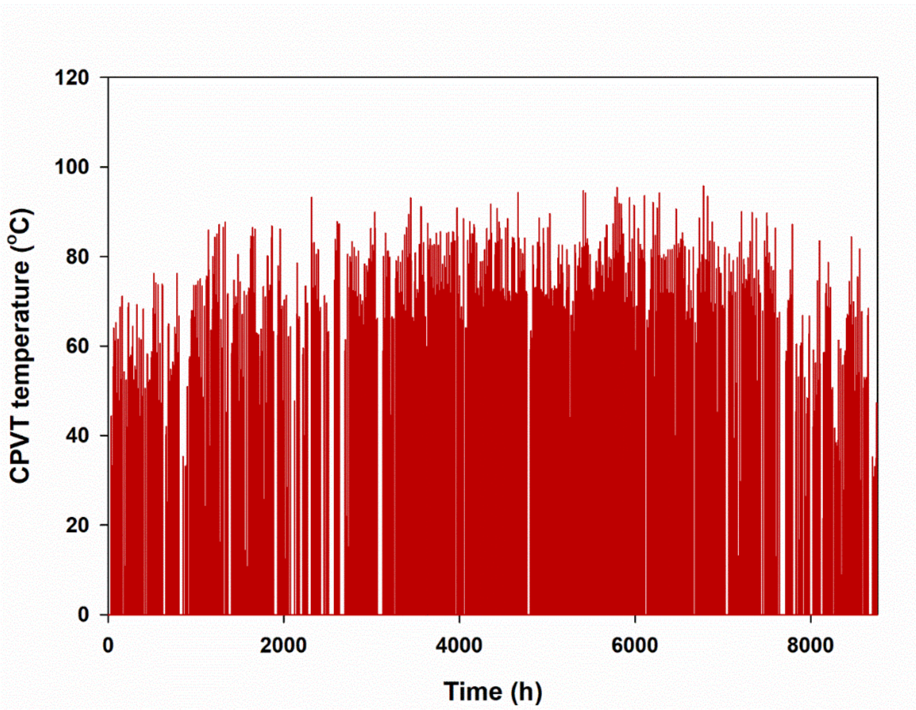

Fig. 6. Simulated hourly CPVT operating temperature

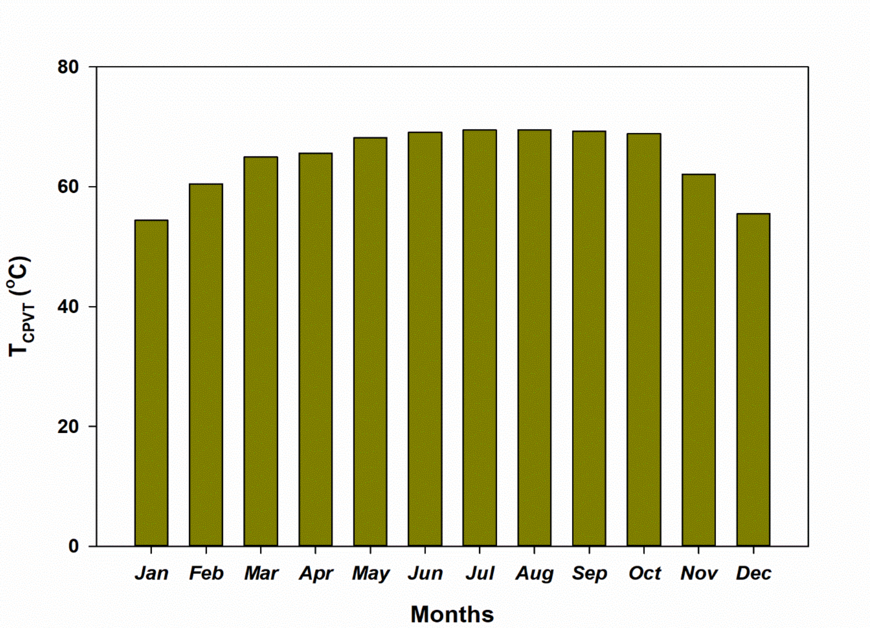

Fig. 7. Monthly operating temperature of CPVT collector

In the present study, the produced thermal energy by CPVT system is utilized for space heating and DHW. It can also be used for driving an absorption chiller in the air-conditioning system, industrial applications and seasonal thermal storage. The solar fraction (*SF*) represents a portion of the thermal energy demand which is provided by solar energy. The total *SF* calculated by Eq. (1) indicates the portion of required residential heat is produced by the CPVT system. Solar thermal energy supplied by CPVTs, energy generated by the auxiliary system and the calculated values of *SF* are shown in Fig. 8.

The lowest SF value occurs in January which 32% of the residential heating demand can be produced by the CPVT system (Qaux = 2368 kWh, Qsol = 1115 kWh). The ambient temperatures and solar irradiance is low in January, therefore SF is minimum. The maximum monthly total SF that occurs for August in Isfahan is 100% which 804 kWh of required heat provided by the CPVT system.

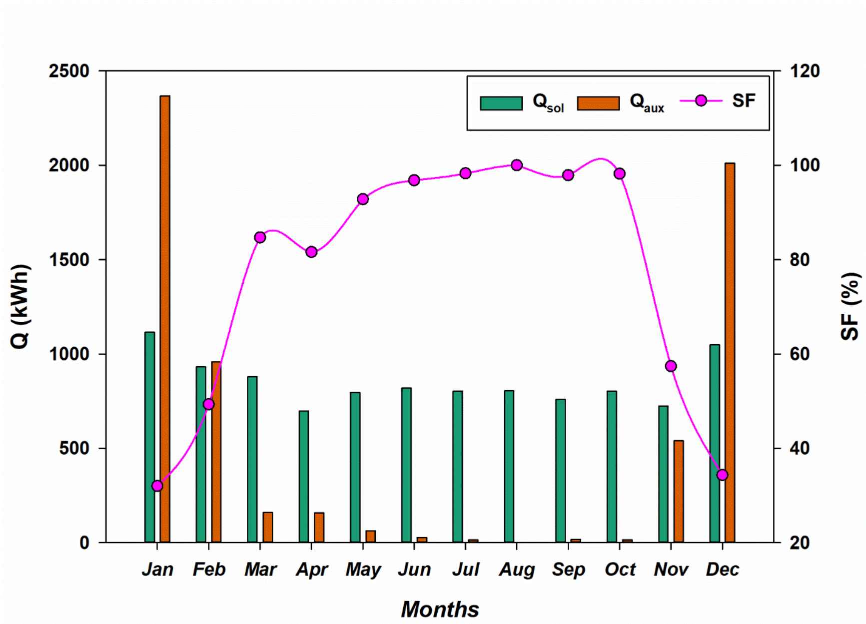

Fig. 8. Solar heat, auxiliary heat and solar fraction

The lowest *SF* values (34.3%, 32%, and 49.3%) supplied by the CPVT system will be in the winter season (December, January, and February). In summer months including June, July, and August, the CPVT system provides 96.8%, 98.3%, and 100%, respectively, of required residential heat. Therefore, during the coldest months in winter, less than 39% of the required heat can be provided by the solar thermal segment of the CPVT system, because space heating load is added during winter. For 5 kWp PVT system with flat plate collectors installed in Isfahan, less than 15% of residential heating of the building is supplied by collectors [39].

Electrical energy is another useful energy produced by CPVT hybrid systems. The monthly AC electrical energy output from the inverter along with solar radiation onto the module area ($E_{sol\,PV}$) are shown in the Fig. 9. The maximum total solar radiation on to the module area is 12459 kWh which occurs during July. Also, 8368 kWh of solar energy is irradiated to the modules in December .The GC-CPVT system generates maximum and minimum amount of electrical energy in June (E_{AC}=1030.9 kWh) and December (E_{AC}=782.1 kWh), respectively. The maximum AC electrical output energy from a 5 kWp flat plate PVT system was obtained 833 kWh [39].

In this section, performance criteria of grid-connected PV modules, i.e. Y_R, T_F and *PR*, are investigated for the GC-CPVT system. Figure 10 depicts the monthly Y_R and Y_F to investigate the *PR* of the GC-CPVT system. The variation of Y_R value depends on the solar irradiance on the CPVT receivers at various months. The lowest value of Y_R is 170.28 kWh/kWp which arises in December. It is clear from Fig. 9 the solar irradiance on the module area ($E_{sol\,PV}$) is 8367.9 kWh in December. Figure 4 also indicates the minimum GHI and DNI is detected in December. This Y_R is equivalent to produce 782.1 kWh energy by the inverter. Performance ratio (*PR*) is another indicator to assess the performance of the PV module of the CPVT system. Figure 10 also displays the variation of *PR* in different months. The closer the *PR* is to 100%, the lower the difference between Y_R and Y_F, so the performance of the GC-CPVT system is close to ideal. For the investigated GC-PVT system, the monthly *PR* varies from 70.3% in August to 82.2% in January. The *PR* indicator is employed to compare the performance of various GC-PV systems independent of rated power, installation location, angle and direction [43].

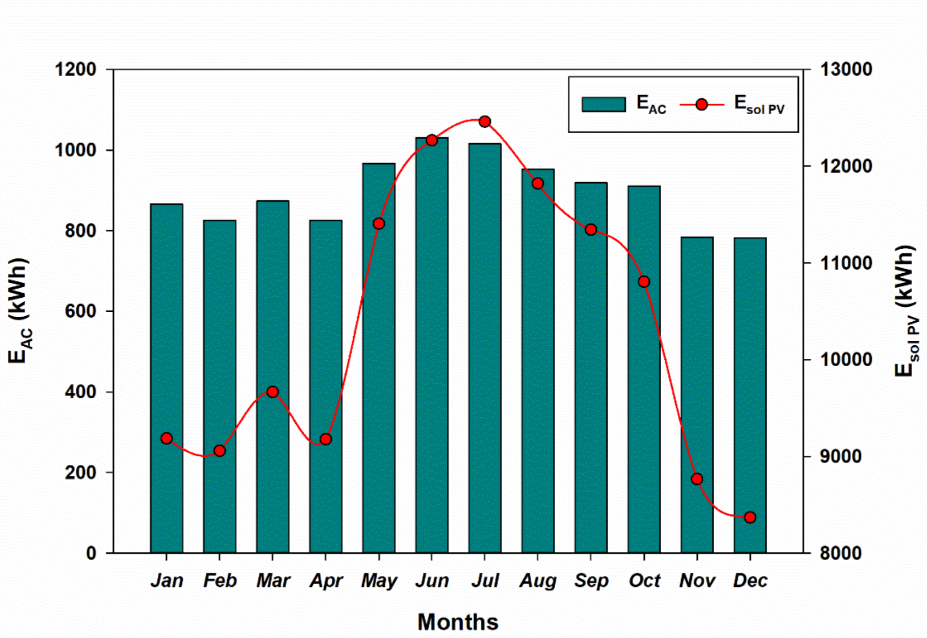

Fig. 9. Monthly AC electrical energy produced by CPVT system and radiation on to the module area

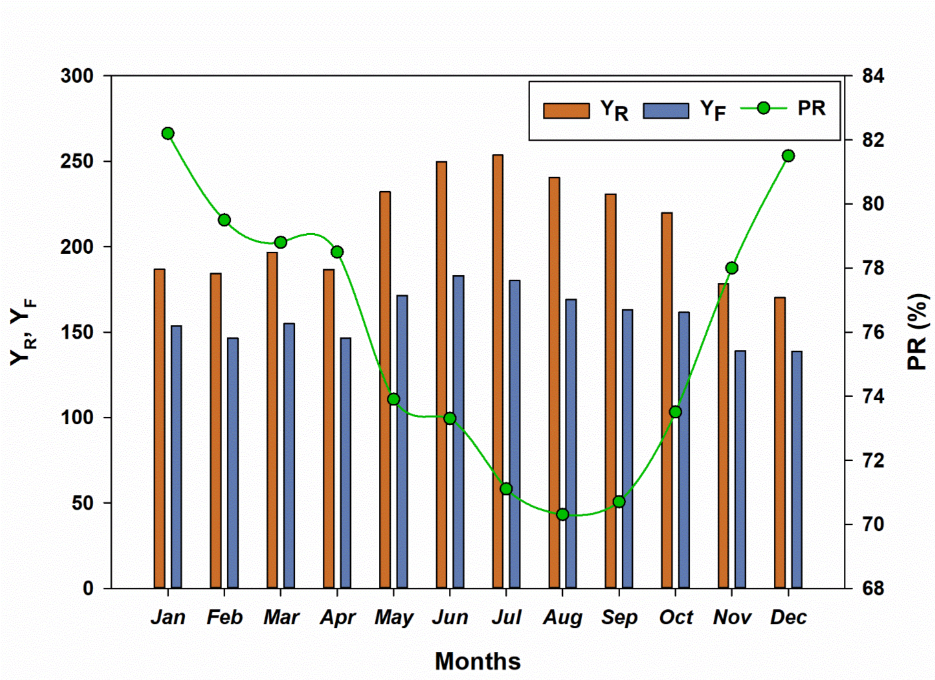

Fig. 10. Variations of monthly YR, YF and PR

Annual parameters indicating the performance of GC-CPVT system are listed in Table 6. Solar thermal production is 10179 kWh which is equivalent to saving 855 m^3 of natural gas. The annual SF value for Isfahan is 61.7%. The value of SF and Y_F for a 5 kW flat GCPVT system in Isfahan were obtained as 45.6% and 1757 kWh/kWp, respectively [39]. It is worth mentioning that the annual SF values for covering DHW and space heating are achieved 78.3% and 35.3%, respectively. The GC-CPVT system is more efficient than a similar GC-PVT system.

Table 6. Annual performance parameters of the GC-PVT system

Parameter	Value	Unite
Q_{sol}	10179	kWh
Q_{aux}	2368	kWh
SF	61.7	%
SF (DHW)	78.3	%
SF (Building)	35.3	%
E_{AC}	10752.1	kWh
Y_R	2529.9	kWh/kW
Y_F	1908.4	kWh/kWp
PR	75.4	%

4.2. Environmental investigation of GC-CPVT system

Conventional methods for generating electricity and heat usually utilize fossil fuels. Carbon dioxide (CO_2) is one of the combustion products of fossil fuels that play a major role in environmental pollution and global warming. The application of PVT solar systems, especially in buildings, can significantly reduce CO_2 emissions and cost issues [44].

Figure 11 illustrates the hourly amount of CO_2 produced by some components of GC-CPVT system including pumps and auxiliary boiler. On cold winter days, the energy produced by the auxiliary boiler is needed and the GC-CPVT system produces a small amount of CO_2.

Figure 12 shows the monthly CO_2 emission reductions with the bar graph. As can be seen, the PV module has the greatest impact on CO_2 emission reductions, which is the highest value in July (545 kg CO_2) and the lowest value (419 kg CO_2) in December. About 27-38% of the CO_2 emission saving is related to the solar thermal part. For the city of Isfahan by installing the mentioned GC-CPVT system, it can be prevented an annual average of 8386 kg CO_2 emission. Assuming the system has a lifespan of 25 years, for each hybrid system, more than 200 tons of CO_2 emissions will be saved. Using the definition of CO_2 specific emission factor, i.e., the amount of CO_2 emitted per 1 kWh of energy produced, it can be said that an average of 0.40 kg CO_2 is saved per kWh of energy (electrical and thermal) generated by the GC-PVT system. For the thermal part, this factor is 0.26 kg CO_2/kWh. This value is reported to be 0.297 kg CO_2/kWh for building-integrated PVT systems in Hong Kong [45]. In Iran, the CO_2 specific emission factor in the power sector is 571.29 g/kWh [46].

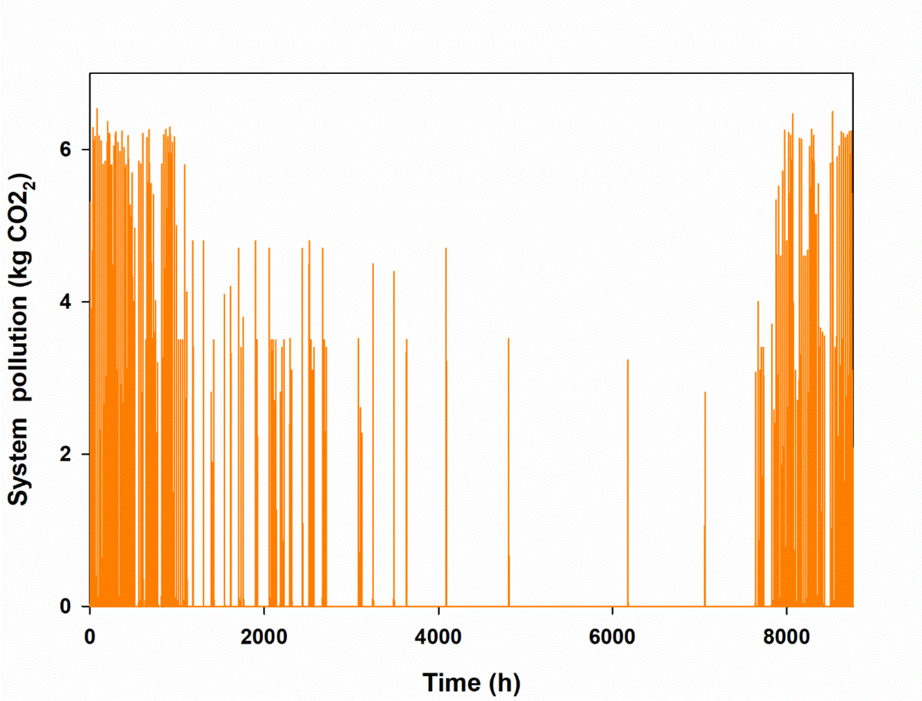

Fig. 11. GC-CPVT system CO_2 emission

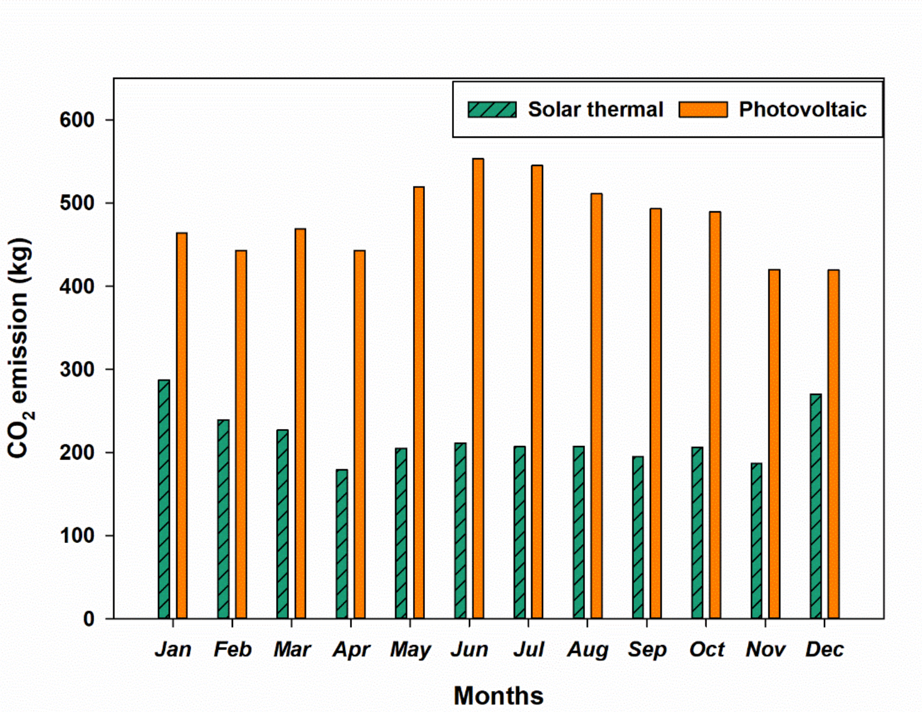

Fig. 12. Monthly reduction in CO_2

5. Conclusions

This paper evaluated the performance of a GC-CPVT system generating GC electricity and residential heat in the city of Isfahan, Iran. The system was a 5.63 kWp ground-mounted CPVT system. The remarkable achievements of the study are:

- The GC-CPVT system is very efficient for the simultaneous generation of electricity and heat from solar energy .
- The hybrid system with concentrating collector can annually produce more than 10000 kWh AC electricity. This amount of electrical energy makes the yield factor criterion very competitive for this system. The annual Y_f is around 1900 kWh/kWp.
- The amount of performance ratio is very close to 100% and therefore it can be concluded that the system is close to the ideal state. It was in the range of 70.3% to 82.2%.
- The hybrid GC-CPVT system provides most of the thermal energy required for DHW and space heating. So that, the solar fraction was 78.3% for DHW supply and 35.3% for space heating.
- The proposed hybrid system can help preserve the environment by reducing CO_2 emissions. An average of about 8386 kg CO_2 emission was annually prevented by installing a GC-CPVT system.

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