Renewable Energy 130 (2019) 524–535

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Comparative study of solar-powered underfloor heating system performance in distinctive climates

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ARTICLE INFO

Article history:
Received 25 December 2017
Received in revised form
29 May 2018
Accepted 19 June 2018
Available online 20 June 2018

Keywords:
DesignBuilder
Economic analysis
Energy performance
Solar energy
Underfloor heating
Building

ABSTRACT

According to the International Energy Agency, buildings are the largest energy-consuming sector globally, producing over one-third of greenhouse gas emissions in 2013. Renewable energies such as solar can be harnessed to fully or partially meet the energy demands of buildings. In this study, solar thermal collectors are used in a building to provide the hot water required for an underfloor heating system. Three cities in Iran, namely Tabriz, Tehran and Kish island, with distinctive climatic conditions are considered to gain a better understanding of the performance of solar-powered underfloor heating systems in different climates. Moreover, an economic analysis is conducted to assess the feasibility of the proposed system. DesignBuilder software is applied to simulate the energy performance of the building. The results indicate that the annual fuel consumption of the building with a solar collector located in Tehran, Tabriz and Kish island is reduced by 125.39, 303.58 and 1.41 MWh compared to that of without collector, respectively. The payback period of the system for Tehran, Tabriz and Kish Island is found to be 8.2, 9.4 and 12.1 years, respectively.

1. Introduction

Depletion of fossil resources, global warming, industrialization and growing population pose challenges to the energy sector [1–3]. The building sector presently accounts for approximately 40% of global energy consumption, producing 30% of annual greenhouse gas (GHG) emissions in 2013 [4,5]. Renewable energies such as solar can be harnessed to meet the electricity, heating and cooling demands of buildings using photovoltaic (PV) or solar thermal collectors, with a reduced carbon footprint [6]. Solar thermal systems have been widely used throughout the world for heating and cooling purposes [7–10]. The global installed capacity of solar thermal systems reached 456 GW by the end of 2016 [11].

Heating, ventilation and air conditioning (HVAC) systems are the primary energy consumers in buildings [12,13]. PV and solar thermal systems can be implemented in buildings, to meet some or all of the electrical, heating and cooling demands. However; prior to installation of these systems, the feasibility needs to be assessed in both technical and economic terms to avoid investment risks as well as to ensure the reliability and sustainability of the system.

Much research has been reported on the technical, economic and environmental aspects of buildings integrated with PV and solar thermal systems. A dynamic approach was adopted to investigate domestic hot water (DHW) production using solar thermal collectors [14]. That study showed that the solar coverage factor correlates closely with daily water consumption. The application of phase change materials (PCMs) in evacuated tube solar collectors was examined to enhance the performance of the collectors [15]. The charging efficiency of PCM integrated collectors varies from 30 to 70%, depending on PCM temperature and solar radiation level. The annual solar fraction of these collectors increases by 20.5% compared with conventional solar collectors. To improve the design accuracy of solar water heating systems, Nogueira et al. developed a program in MATLAB that enables users to model different types of solar collectors with auxiliary equipment [16]. The thermal performance of a 4 m^2 solar flat plate collector for water heating was experimentally studied over a one-year period in Dublin, Ireland [17]. The annual mean daily energy, pipe losses and solar fraction were found to be 19.6 MJ/d, 3.2 MJ/d and 32.2%, respectively. The effects of mass flow rate, inlet water

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https://doi.org/10.1016/j.renene.2018.06.074
0960-1481/

Nomenclature

A	Gross area of collector
q	Useful heat gain
F_R	Correction factor
I_{Solar}	Total solar incident radiation
$\tau\alpha$	Transmittance absorptance product
U_L	Overall heat loss coefficient
T_{in}	Working fluid temperature
T_{air}	Ambient air temperature
η	Energy efficiency of solar collector

and ambient temperature and solar insolation on thermal performance of open and closed loop solar water heating systems was examined [18]. That study showed that the efficiency of the system improves with increasing mass flow rate in the solar collectors, ambient temperature and solar insolation.

The techno-economic feasibility was assessed of a solar water heating system used in a hospital laundry in Brazil [19]. The system was found to be economically justifiable. To reduce the heating costs of greenhouses, a solar water heating was proposed for various sizes for greenhouses in Tunisia [20]. The results indicated that the solar system can independently meet the heating requirements as well as reduce heating costs of a 1000 m^2 greenhouse by 52% in April. A techno-economic study was conducted to select the optimal solar water heating system in Saudi Arabia [21]. The study demonstrated that the utilization of evacuated tube solar collectors in the cities of Gaseem, Dhahran and Riyadh is highly beneficial economically. To mitigate the energy consumption for air conditioning in Saudi Arabia, Al-Ugla et al. examined three types of air conditioning systems: conventional vapor-compression, PV vapor-compression and solar LiBr-H_2O absorption [22]. In the study, a typical large scale commercial building in Saudi Arabia with constant diurnal cooling was investigated considering two economic indicators, i.e., payback period and net present value (NPV). The solar absorption system was seen to outperform the solar PV-vapor-compression system economically. It was also found that, with increasing electricity rates and building size, the solar systems become more cost effective. Zainine et al. simulated a solar water heating system in TRNSYS software to find the optimal flow rate and conducted an economic analysis [23]. The economic analysis demonstrated that the solar water heating system is economically viable. A solar water heating system applied in a high-rise building in China was analyzed [24]. It was found that the system is reliable and economically feasible. Cassard et al. investigated the technical and economic performance of rooftop solar water heating systems located in the USA [25]. The study revealed that the utilization of these systems can reduce fuel heating loads by 50–85% per year. Buonomano et al. introduced a novel flat plate solar collector that made up of inexpensive materials to be integrated in buildings. The energy, comfort, environmental and economic performance of the system was evaluated considering diverse climatic conditions in different regions [26]. The system was found to be economically viable for space heating and DHW provision. A genetic algorithm (GA) with the objective of maximization of life cycle savings was adopted to optimize two predominate factors in the performance of flat plate solar water collector (FPSWC) systems [27]. The economic analysis of the optimal FPSWC verified the feasibility of these systems in all the selected case studies. A multi-objective Particle Swarm Optimization (PSO) method was employed to thermo-economically optimize a flat plate collector water heater [28]. The results indicated that the optimal thermo-economic performance occurs for lower rates of heat transfer.

A solar assisted water and space heating system was techno-economically assessed for an 88 m^2 house taking into account four distinctive climatic zones of Greece [29]. The study revealed that even in the worst-case scenario the proposed system can supply 45% of the total heating load as well as reducing CO_2 production by 50t. Moreover, the payback period of the system was found to be 4.5 years for that scenario. Mazarrón et al. examined an evacuated tube collector for active solar water heating systems by considering various operating water temperatures and they exhibited that the efficiency and profitability of the system were negatively impacted by increasing the temperature [30]. However, development of appropriate design and sizing of the system could result in economic benefits for the considered scenarios. The economic and environmental performance of a solar-powered heating system was studied in Algeria and compared to a conventional one [31]. Nevertheless, the massive subsidies of the conventional energy in the country, the solar-powered system was both economically and environmentally beneficial. PV and solar thermal collectors can be coupled to meet heating and electricity demands simultaneously. The energy and exergy performances of a naturally ventilated building-integrated photovoltaic-thermal (BIPV/T) system were experimentally and theoretically investigated [32]. The findings indicate that the energy efficiency fluctuates between 26.5% and 33.5%, and the exergy efficiency between 13% and 16%. Debbarma et al. reviewed the thermal performance of building-integrated photovoltaic (BIPV) and BIPV/T systems and showed that BIPV/T systems are far preferable to BIPV systems since they can meet heating and electricity demands simultaneously, using the same collector area [33].

However, to best of our knowledge, few techno-economic comparative investigations have been reported of solar water heating systems that supply the water required for underfloor heating system. Iran has significant solar resources. However, the solar potential of the country has not yet been fully exploited. In this study, a solar under floor heating system is considered to meet heating demands of a hotel building. The water heated by flat plate solar collectors is used in the heating system to reduce the need for excessive fossil fuels. The performance of solar systems is highly impacted by climatic conditions of the region. Hence, in this study, three cities, Tehran, Tabriz and Kish island, with diverse climatic conditions are selected. We also conducted an economic and environmental assessment in order to evaluate the shift toward solar assisted systems. The building energy performance is simulated in DesignBuilder software. Then, RETScreen software is adopted to assess the economic viability of the system.

2. Methodology

2.1. Building description

A typical hotel building is selected as a case study. The building with a total area of 12,000 m^2, has 6 stories that include the lobby, rooms, a conference room, restaurants, a play area, a gym and an office area. The building specifications and internal gains for the simulated period are summarized in Table 1. A 2D plan of the building is depicted in Fig. 1. The building is simulated in DesignBuilder software, an advanced building modeling tool, for the period of December to February. Conventional construction materials that are available in Iran's market are used in the building. The materials and their properties are listed in Table 2. The window to wall area ratio of the building is taken to be 30%.

To meet heating requirements, an underfloor heating system is implemented in the building. The underfloor system distributes the

Table 1
Building specifications.

Parameter	Value
Building total area	12000 m^2
Activity	Hotel
Glazing type	Double glazing (two 3 mm clear glasses with 13 mm air gap)
Lighting gains	102.20 MWh
Computer and equipment gains	115.32 MWh
Occupancy gains	108.51 MWh

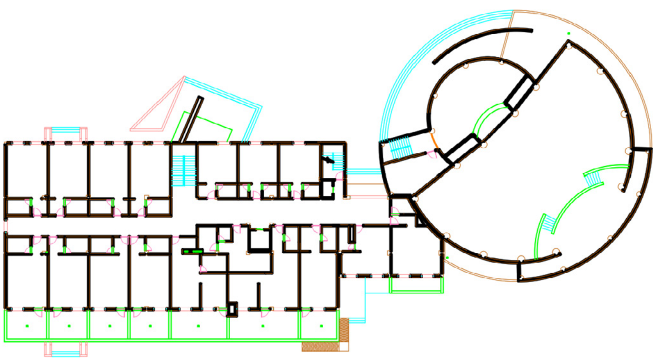

Fig. 1. 2D plan of the building.

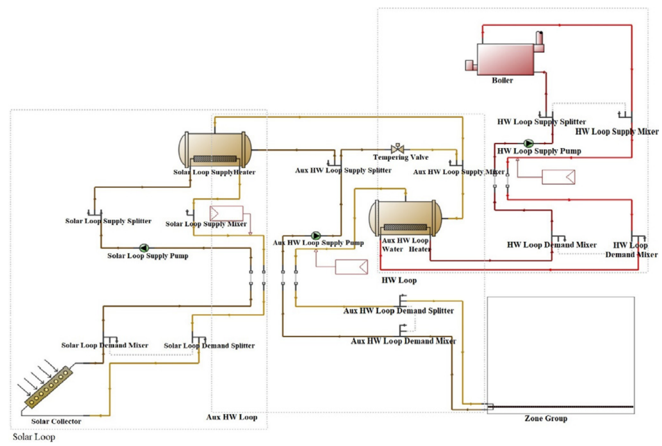

Fig. 2. Schematic of the HVAC system.

heat more evenly throughout the building than most other heating systems. Moreover, the underfloor system requires a water temperature of about 40–50 °C [38] while the other systems such as wall mounted radiators need a water temperature of 60–70 °C [39,40]. To supply the water required for the heating system, solar collectors are coupled with the boiler. A schematic of the HVAC system is given in Fig. 2. The system is composed of three loops: solar, heated floor and hot water loops. A working fluid is heated by the solar collectors. Then, it flows to the solar hot water tank where it is heated and stored. An auxiliary water heater is also used in the system in case the water is not sufficiently hot. To attain the desired temperature, a tempering valve is utilized. The exiting water temperature is set to 45 °C. A back-up boiler, running on natural gas, supplies heat for the auxiliary water heater.

2.2. Solar collector design

A solar thermal system is used in the building to reduce amount of fossil fuel consumed in the boiler. Glazed flat plate collectors with a total area of 968 m^2 are installed on the roof. The specifications of the solar collectors are listed in Table 3. By examining different configurations and shading effects of the collectors, six rows, each with 80 collectors are considered. The building 3D model and the collectors are shown in Fig. 3.

DesignBuilder uses EnergyPlus as its simulation engine, and it is a very accurate and powerful simulation software tool whilst at the same time has a relatively easy to use interface. The EnergyPlus solar collector model is based on the equations of the ASHRAE standards, as well as Duffie and Beckman. The thermal efficiency of the solar collector is the ratio of useful heat gain of the collector on the gross surface area to the total incident radiation and can be written as:

$$\eta = \frac{\frac{q}{A}}{I_{solar}} \quad (1)$$

where q, A and I_{solar} are useful heat gain, collector gross area, and

Table 2
Construction materials of the building.

Component	Material	Thickness (m)	Density (kg/m^3)	Specific heat (kJ/kg.K)	Thermal conductivity (W/m.K)
External walls	Brick work	0.1	1700	800	0.84
	XPS extruded polystyrene - CO_2 blown	0.0795	35	1400	0.034
	Concrete block	0.1	1400	1000	0.51
	Gypsum plastering	0.013	1000	1000	0.4
Internal walls	Gypsum plaster board	0.25	900	1000	0.25
	Air gap	0.1	–	–	–
	Gypsum plaster board	0.25	900	1000	0.25
Roof	Asphalt	0.01	2100	1000	0.7
	MW glass wool (rolls)	0.14	12	840	0.04
	Air gap	0.2	–	–	–
	Plasterboard	0.013	2800	896	0.25
Floor	Urea formaldehyde foam	0.1327	10	1400	0.04
	Cast concrete	0.1	2000	1000	1.13
	Floor screed	0.07	1200	840	0.41
	Timber flooring	0.03	650	1200	0.14

Table 3
Specifications of the solar thermal collectors.

Specification	Characteristic	Value or description
Type	Manufacturer	ACR Solar International
	Model	10–01
	Brand	Skyline
Dimensions	Gross area (sq. ft.)	10.0
	Net aperture area (sq. ft.)	9.12
	Length (in)	72.2
	Width (in)	20.0
	Depth (in)	3.0
Collector performance	Clear (kBtu/day/sq. ft.)	0.83
	Mildly cloudy (kBtu/day/sq. ft.)	0.56
	Cloudy (kBtu/day/sq.ft.)	0.29
Absorber material	Absorber coating	Selective coating
	Tube	Copper
	Plate	Copper fin
	Cover (outer)	Lexan polycarbonate
	Frame	Aluminum

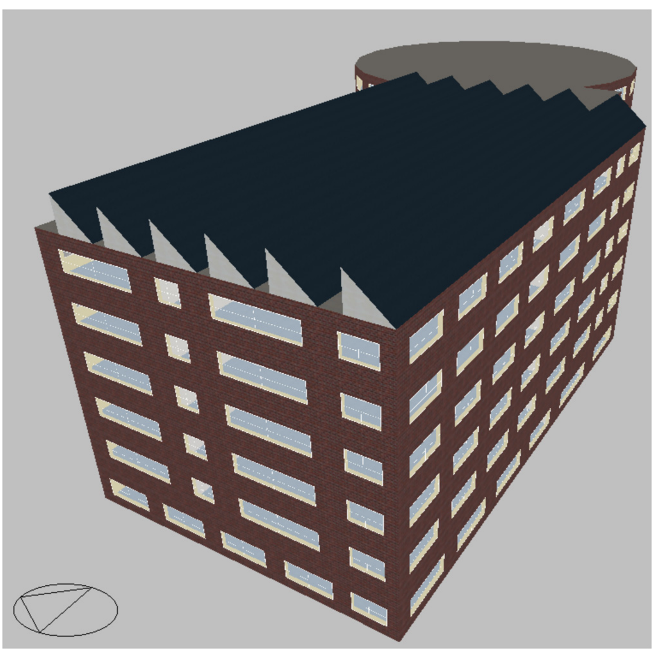

Fig. 3. Building 3D model and the roof top collectors.

total incident solar radiation, respectively.

The energy balance for the collector can be expressed as:

$$\frac{q}{A} = F_R[I_{solar}(\tau\alpha) - U_L(T_{in} - T_{air})] \quad (2)$$

where F_R is an empirically determined correction factor. $\tau\alpha U_L$, T_{in} and T_{air} denote transmittance-absorptance product, overall heat loss coefficient, inlet temperature of working fluid and ambient temperature, respectively. Using Eq. (2), efficiency can be written as:

$$\eta = F_R(\tau\alpha) - F_R U_L\left(\frac{T_{in} - T_{air}}{I_{solar}}\right) \quad (3)$$

Considering $F_R(\tau\alpha)$ and $F_R U_L$ as the characteristic constants of the collector, the following linear correlation is constructed:

$$\eta = c_0 + c_1\left(\frac{T_{in} - T_{air}}{I_{solar}}\right) \quad (4)$$

A quadratic correlation can also be used:

$$\eta = c_0 + c_1\left(\frac{T_{in} - T_{air}}{I_{solar}}\right) + c_2\left(\frac{(T_{in} - T_{air})^2}{I_{solar}}\right) \quad (5)$$

The coefficients are reported in the directory of SRCC Certified Solar Collector Ratings. c_0, c_1 and c_2 for the considered collectors are 0.603, −3.867 W/m^{2}K and 0.0015 W/m^{2}K^2, respectively.

2.2.1. Validation

EnergyPlus results for flat plate solar collectors were compared with the results obtained from TRNSYS Type 1 which simulates flat plate collectors based on the equations of the ASHRAE standards, as well as Duffie and Beckman. EnergyPlus results agree very well with TRNSYS for most conditions, except for very low incident angles where only negligible differences were observed.

3. Climatic and solar radiation data

To generalize the findings of this study, three cities in Iran namely Tehran, Tabriz and Kish island, with distinctive climatic conditions, are considered. Climatic information for the cities is summarized in Table 4. The monthly direct normal and diffuse horizontal solar radiation of Tehran, Tabriz and Kish Island are given in Figs. 4–6, respectively. As shown in the figures, the maximum solar direct normal radiation occurs in June for the three

Table 4
Climatic information of selected cities.

City	Latitude (°)	Longitude (°)	Altitude (m)	Maximum dry bulb temperature in summer (°C)	Maximum wet bulb temperature in summer (°C)	Minimum dry bulb temperature in winter (°C)	Minimum wet bulb temperature in winter (°C)
Tehran	35.41	51.19	1190	37.2	18.7	−1.3	−1.3
Tabriz	38.05	46.17	1361	34	16.2	−8.5	−8.5
Kish island	27.13	53.58	9.8	40.1	25.2	10.9	10.9

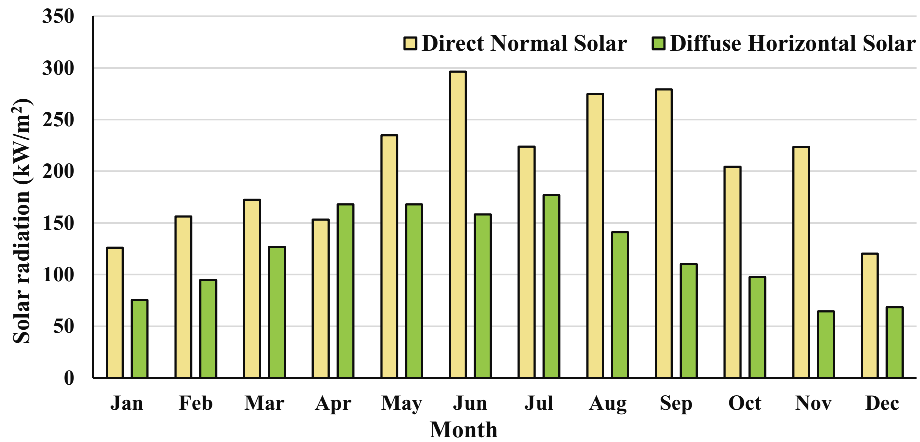

Fig. 4. Monthly direct normal and diffuse horizontal solar radiation for Tehran.

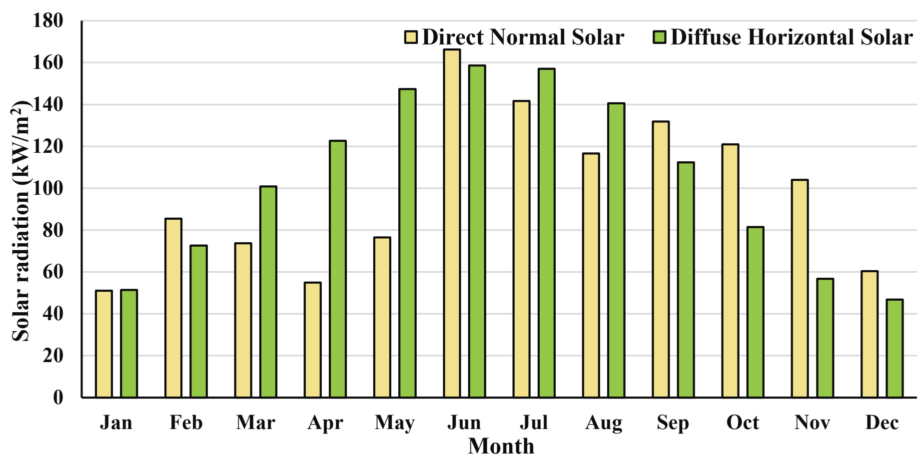

Fig. 5. Monthly direct normal and diffuse horizontal solar radiation for Tabriz.

cities while the minimum occurs in December for Tehran and Kish island and in January for Tabriz. The highest solar diffuse horizontal radiation is observed in July for Tehran, in June for Tabriz and in May for Kish island, whereas the lowest is observed in December for Tabriz and Kish island and in November for Tehran.

4. Results and discussion

After having simulated the building in DesignBuilder software, we present and discuss the results in this section.

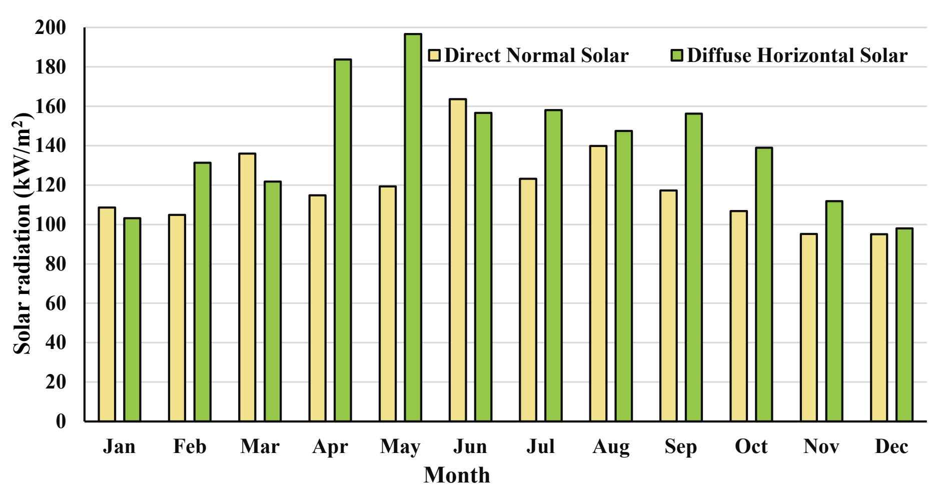

Fig. 6. Monthly direct normal and diffuse horizontal solar radiation for Kish island.

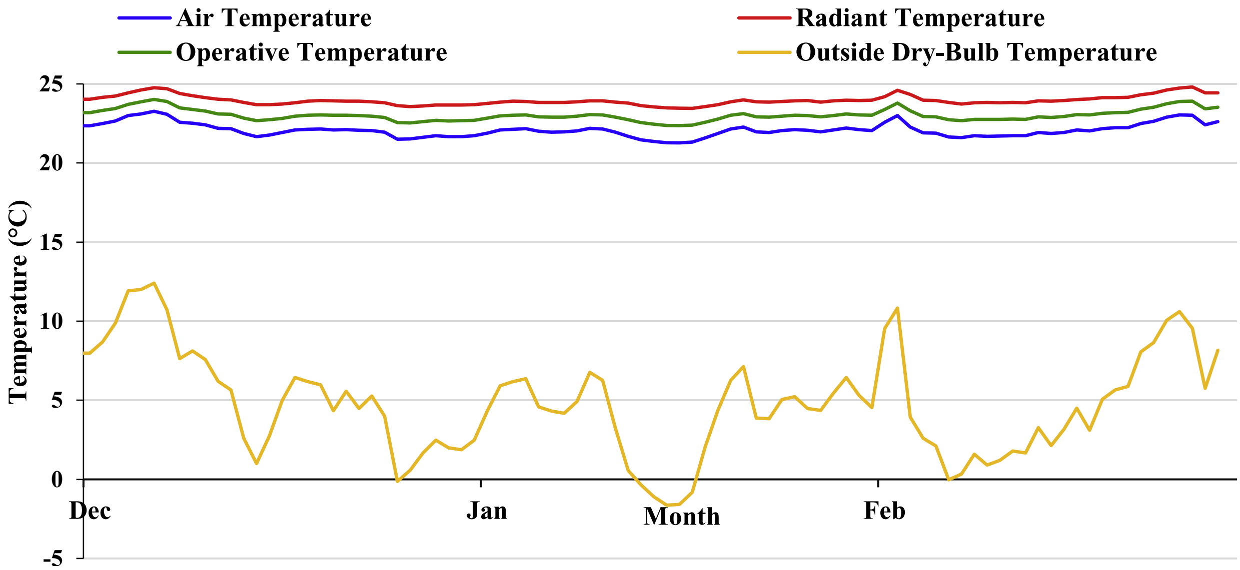

Fig. 7. Zone temperatures for the conventional underfloor heating system in Tehran.

4.1. Simulation results

Zone temperatures, including air, radiant and operative temperatures, as well as the dry-bulb temperature outside the building, are presented in Figs. 7–12 for systems with and without solar collectors and for the three cities considered. The air temperature is the zone temperature determined by the software. The radiant temperature is the weighted average of the zone inside surface temperatures. The operative temperature is the average of the radiant and air temperatures. The air, radiant and operative temperatures for the building in Tehran, as depicted in Figs. 7 and 8, for the conventionally heated building located are in the range of 20–25 °C and for the building with solar collectors fluctuate between 8 and 25 °C. As shown in Figs. 9 and 10, the temperatures for the conventional building in Tabriz vary between 20 and 25 °C and for the building with solar collectors range from 8.5 to 25 °C. Figs. 11 and 12 show the temperatures for Kish Island. For both buildings, i.e., with and without solar collectors, the temperatures vary from 23 to 30 °C. Since solar radiation varies throughout the year and reaches its minimum in January, the temperatures in the building with solar collectors, particularly in Tehran and Tabriz as illustrated in Figs. 8 and 10, undergo a significant fluctuation, follow-up by a dramatic decrease in January.

It is observed in all cases that the building integrated with solar collectors is more liable to thermal fluctuations while the conventional system is capable of keeping the temperatures within the comfortable levels during the simulation period.

Efficiency of the solar collectors are found to be 37%, 35% and 39% for Tehran, Tabriz and Kish island, respectively. The solar fraction for Tehran and Tabriz are equal to 53% and 47%, respectively, while for Kish island, the solar thermal collectors can supply 100% of heating energy without any auxiliary heaters, primarily due to its limited heating demand.

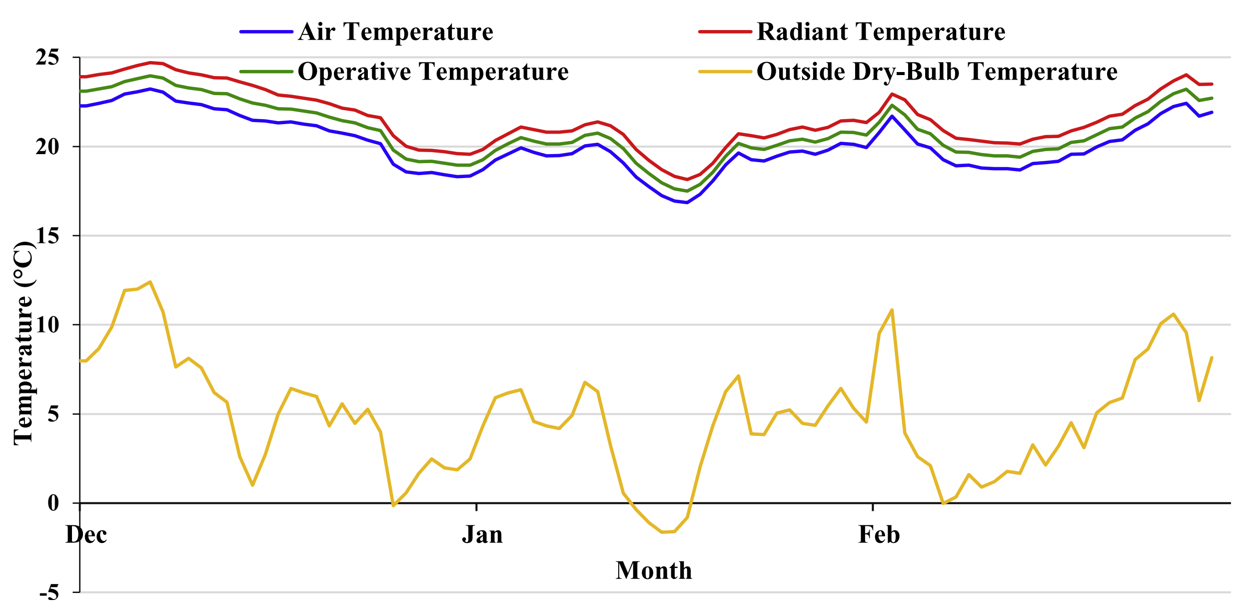

Fig. 8. Zone temperatures for the solar powered underfloor heating system in Tehran.

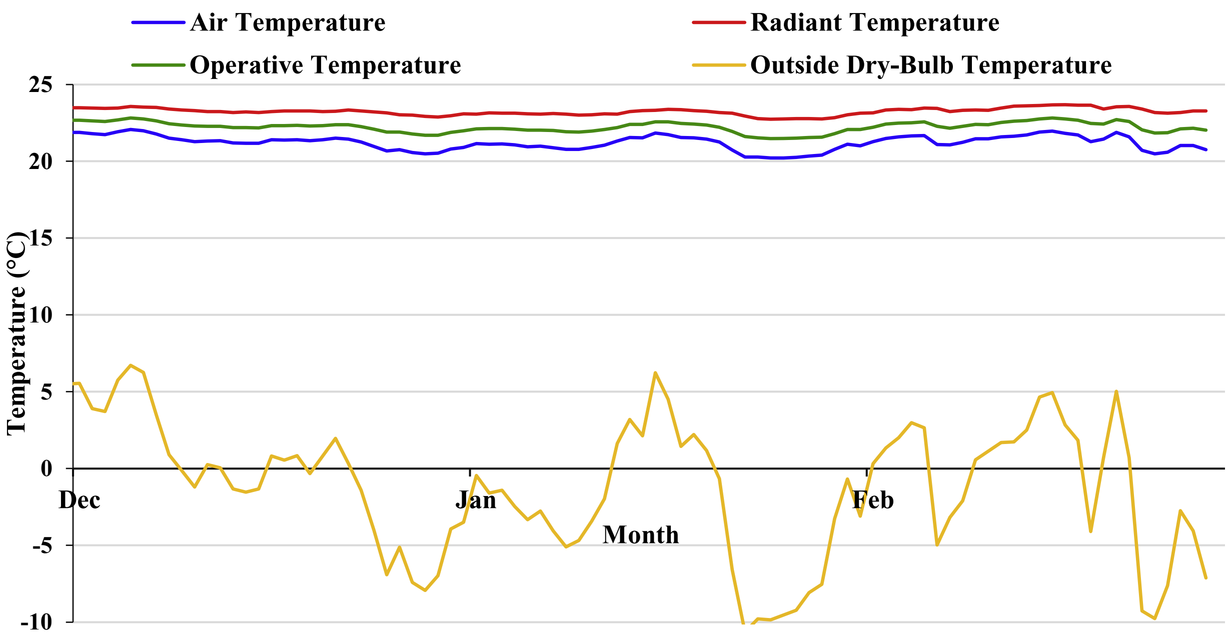

Fig. 9. Zone temperatures for the conventional underfloor heating system in Tabriz.

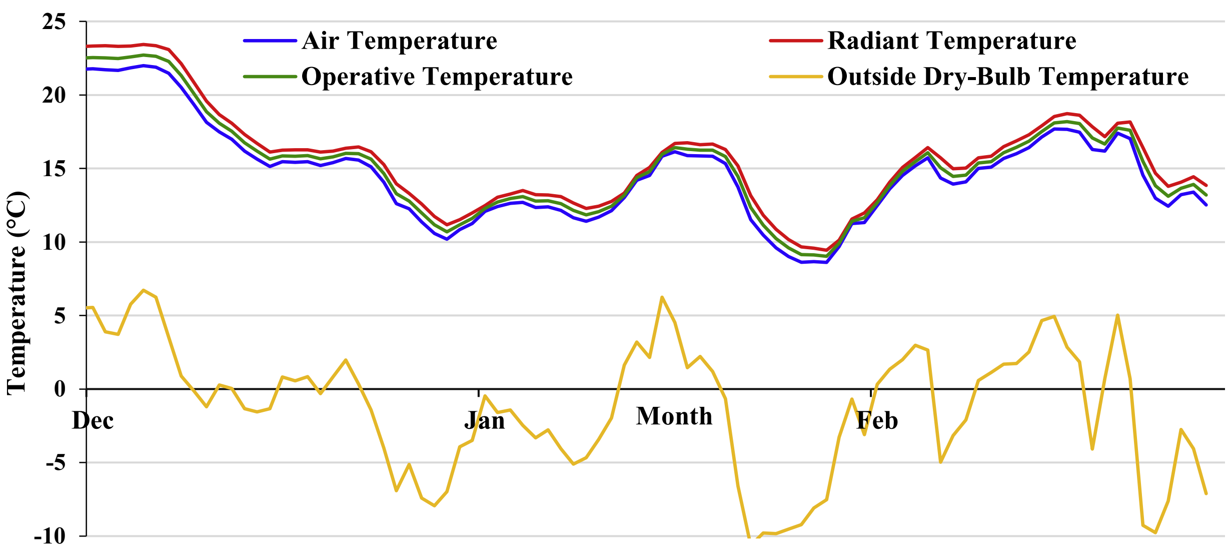

Fig. 10. Zone temperatures for the solar powered underfloor heating system in Tabriz.

4.2. Fuel consumption and CO_2 emissions

The annual gas consumption of the building without and with solar collectors over the simulation period is shown in Figs. 13 and 14, respectively. The gas consumption of Tehran, Tabriz and Kish island is reduced respectively by 125.39, 303.58 and 1.41 MWh during a year through use of the solar collectors. For Tehran, solar collectors can significantly decrease the fuel consumption. Tabriz has a cold semi-arid climate and requires more heating than the other cities. Therefore, the utilization of a solar-powered underfloor heating system can significantly lower fuel consumption in that city. However, Kish island with a hot, semi-equatorial climate, has the minimum heating load and, therefore, solar collectors can satisfy the entire heating load.

The amount of CO_2 produced by the building with and without solar collectors is shown in Fig. 15. The annual CO_2 emissions in Tehran, Tabriz and Kish island respectively for the buildings without solar collectors are 155.44, 188.93 and 132.08 tonnes and for the buildings with solar collectors are 132.6, 132.9 and 131.82 tonnes. Utilizing solar collectors allows the CO_2 emissions to be reduced by 22.84 tonnes in Tehran, 56.03 tonnes in Tabriz and 0.26 tonnes in Kish island.

4.3. Economic assessment

In this section, the economic performance of solar-powered underfloor heating system under different climatic conditions is presented. To assess the economic feasibility of these systems, several factors including capital cost, installation cost, operation and maintenance costs (O&M) and inflation rate are taken into

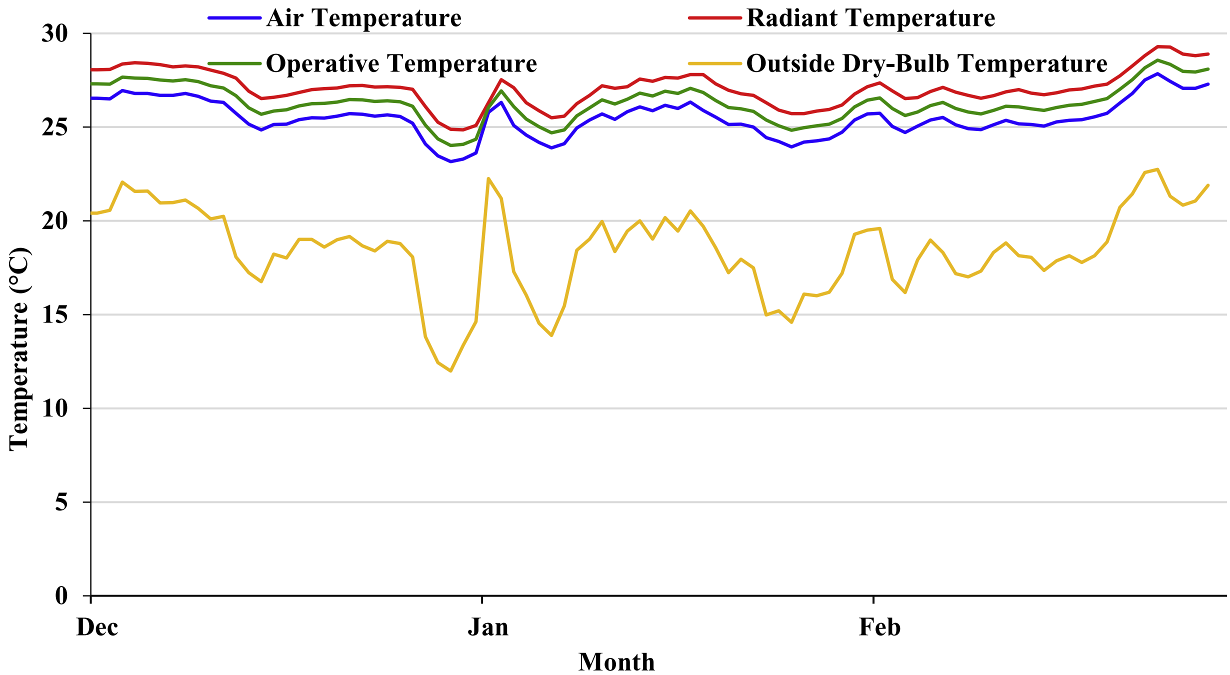

Fig. 11. Zone temperatures for the conventional underfloor heating system in Kish island.

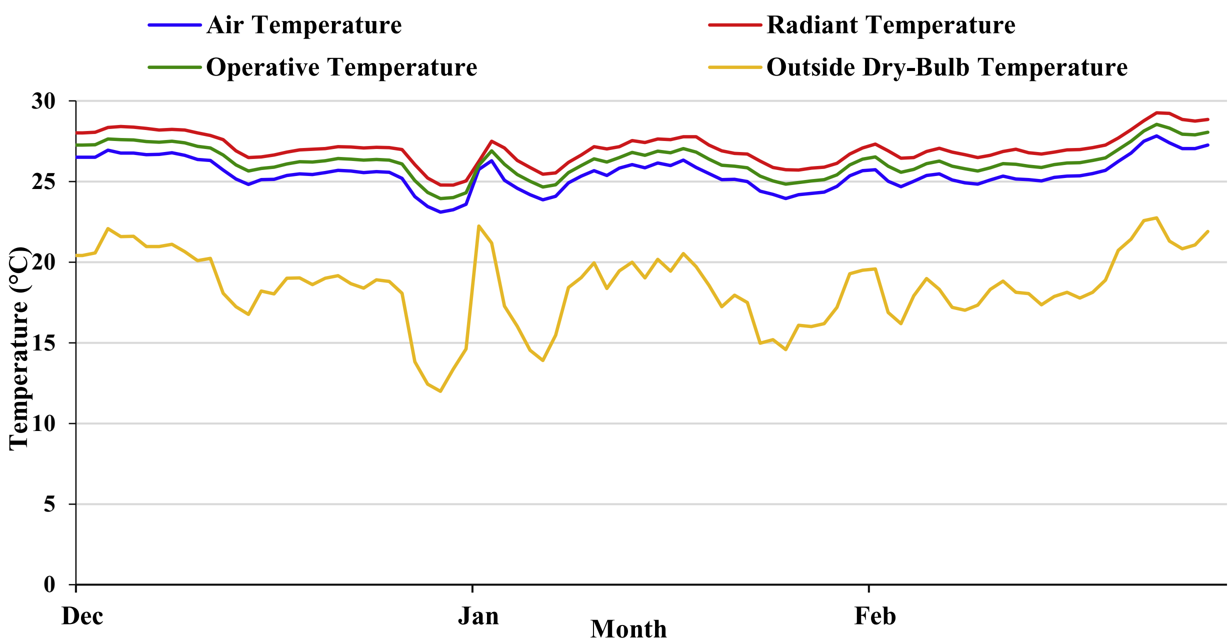

Fig. 12. Zone temperatures for the solar powered underfloor heating system in Kish island.

account. The lifespan of the system is taken to be 25 years. The capital cost is $108,560. Note that monetary units in this article are in 2017 US dollars. The O&M cost is taken to be 30% of the capital cost. The real interest rate which is the difference between inflation rate and interest rate, is assumed to be 2% [42]. The land rent costs are excluded since the solar collectors are installed on the roof of the building and do not occupy any other areas. RETScreen software is applied to assess the economic performance of the solar-powered system. The cost of natural gas in Iran for high consumption buildings is 0.0151 $\$/m^3$ and for low consumption buildings is 0.0129 $\$/m^3$. Thus, the utilization of solar thermal collectors reduces natural gas costs for consumers [43]. However, it should be noted that due to utilization of auxiliary water heaters, the electricity consumption slightly rises in Tehran and Tabriz. However, the building located in Kish island requires no auxiliary heater because of its limited heating demand and warm climate.

As shown in Figs. 16–18, the payback period for Tehran, Tabriz and Kish Island are found to be 8.2, 9.4 and 12.1 years, respectively. The payback period is longer for Kish island since the island has a warm climate and requires less heating. Net Present Value (NPC) is

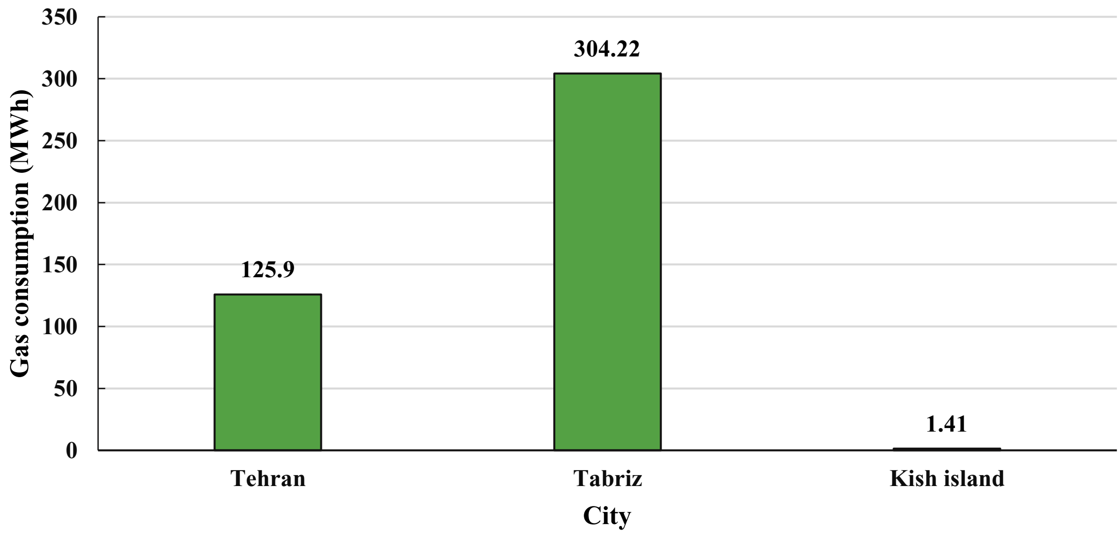

Fig. 13. Annual fuel consumptions of the buildings without solar collectors for the cities considered.

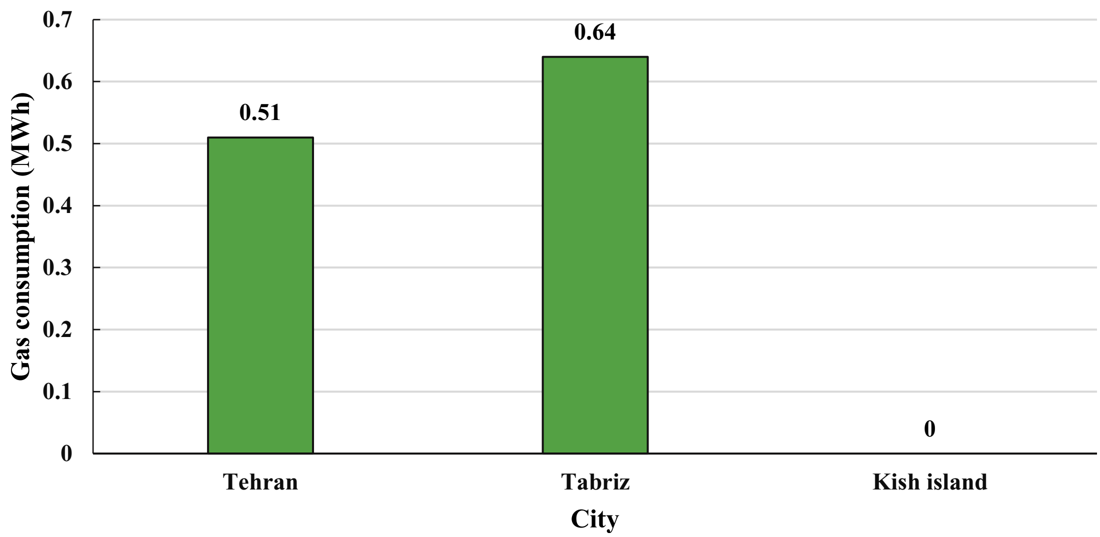

Fig. 14. Annual fuel consumptions of the buildings with solar collectors for the cities considered.

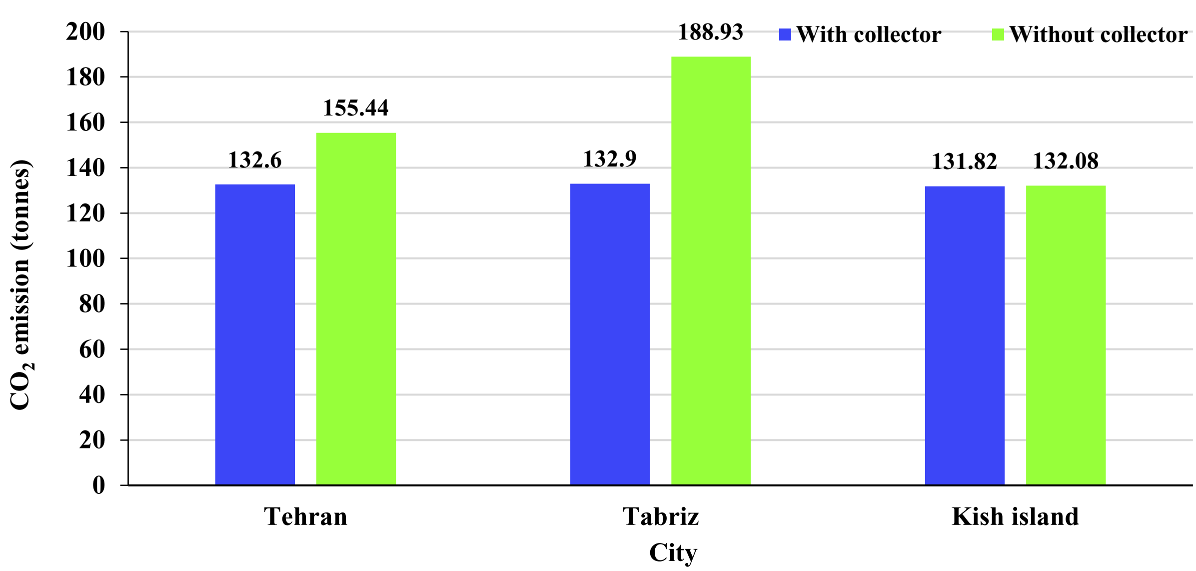

Fig. 15. CO_2 emissions of the buildings with and without solar collectors for the cities considered over the simulation period.

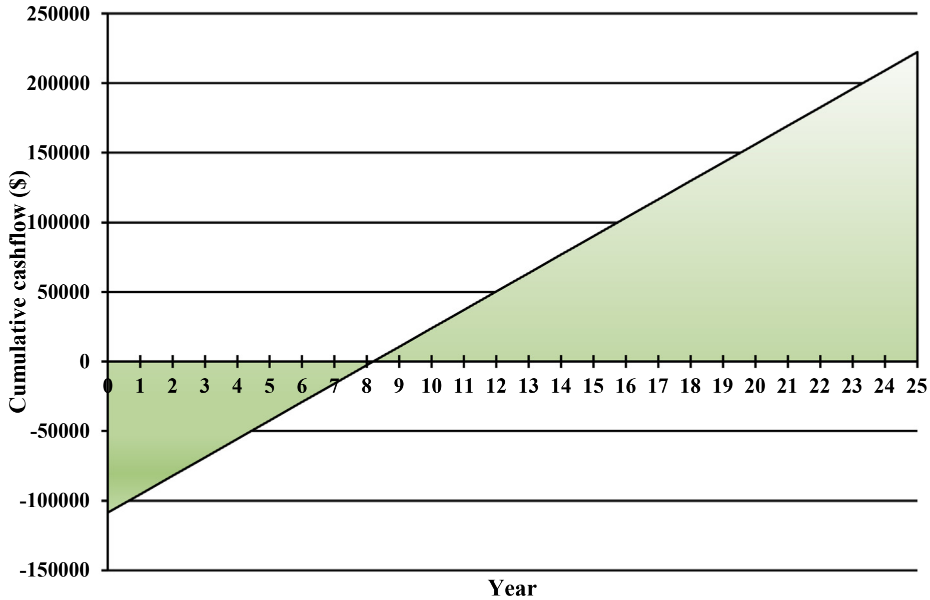

Fig. 16. Payback diagram for Tehran.

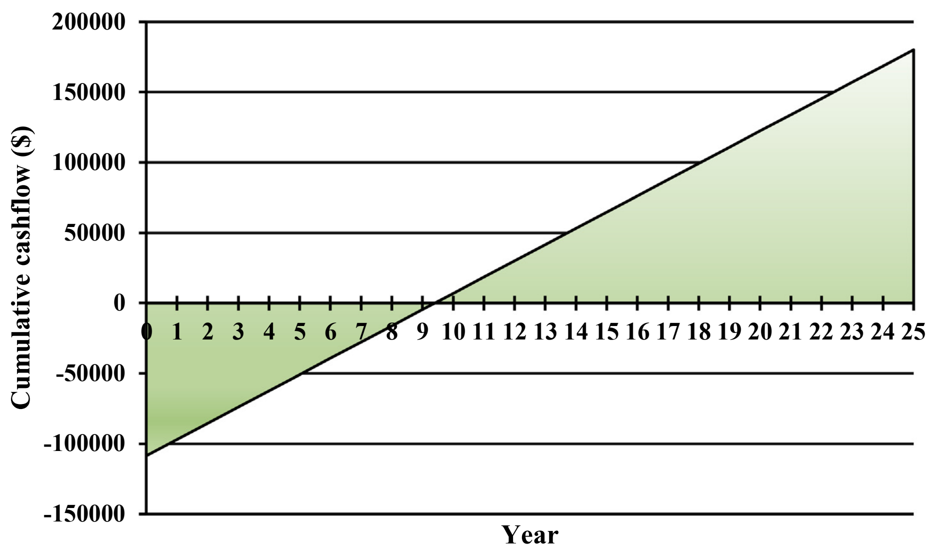

Fig. 17. Payback diagram for Tabriz.

also found to be $146,972, $114,622 and $65,296.58 for Tehran, Tabriz and Kish island, respectively. Considering the technical, environmental and economic aspects, the utilization of solar-powered underfloor heating systems is highly beneficial for Tehran and Tabriz.

5. Conclusions

In this study, the feasibility of solar-assisted underfloor heating systems was assessed for three cities of Iran with distinctive climates. A building with and without solar thermal collectors was simulated in DesignBuilder software. Then, an economic assessment was carried out to assess the feasibility of utilization of the aforementioned systems. The following conclusion can be drawn from the findings:

- The indoor air temperature of the building integrated with solar collectors located in Tehran and Tabriz, is liable to fluctuations. However, for Kish island, the temperature remains constant.
- The utilization of solar-powered underfloor floor heating can reduce the annual fuel consumption by 125 MWh in Tehran, 300 MWh in Tabriz and 1.4 MWh in Kish island.
- During the lifespans of the building systems, over 570 tonnes in Tehran, 1400 tonnes in Tabriz and 6.5 tonnes in Kish island of GHG emissions can be avoided by using solar collectors.
- The payback periods of the solar-powered system for Tehran, Tabriz and Kish island are 8.2, 9.4 and 12.1 years, respectively.

Overall, it can be concluded that the solar-powered heating system outperforms the conventional one since it requires less fuel and reduces GHG emissions. However, the system performs better

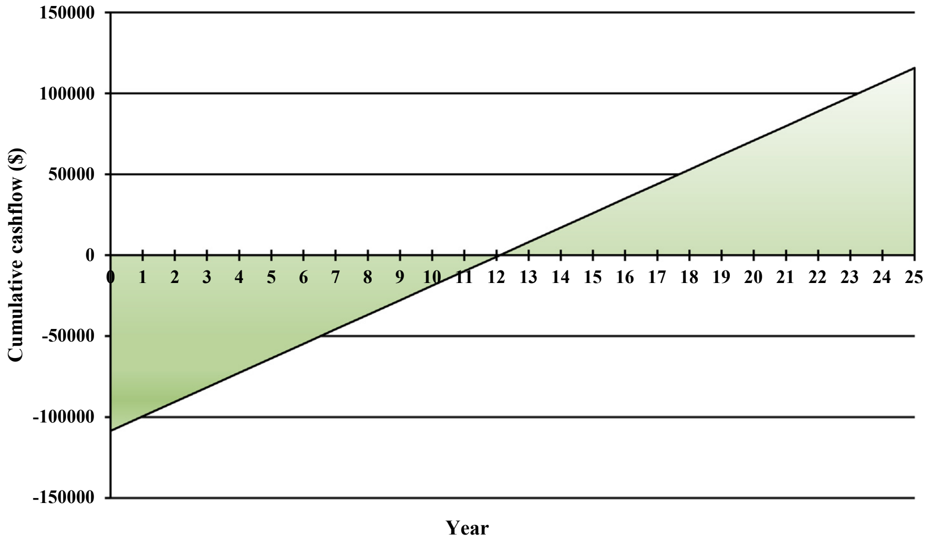

Fig. 18. Payback diagram for Kish island.

in cold climates, when considering the economic, technical and environmental aspects. Future studies appear to be merited that consider different types of solar thermal collectors, the possibility of incorporating solar cooling in the building, and the use of PVT systems in the building to simultaneously meet the heating and electrical demands.

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