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Techno-economic assessment of solar water heating systems for sustainable tourism in northern Pakistan

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KEYWORDS

Solar water heating, solar fraction;
Economic analysis;
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Abstract This study is designed to examine the feasibility of the solar water heating (SWH) system for sustainable tourism in Gilgit-Baltistan (GB) of Pakistan and a tourist resort is taken as a base case. Hot water demand, solar irradiance and economic feasibility are the key parameters considered to investigate the potential of SWH systems using simulation tool T*SOL. Three different types of solar collectors were investigated, based on solar fraction, maximum collector temperature and overall system efficiency. Among these collectors, the evacuated tube collectors (ETC) show high solar fraction, efficiency and CO_2 emissions saved as compared to flat plate collectors (FPC) and unglazed collectors (UnGC), for both locations. The ETC shows 75 % solar fraction, 40 % efficiency, and 676 kg CO_2 emission saved and payback period of is recorded 6.6 years for Gilgit. While for Skardu, 84 % solar fraction, 36 % efficiency, 756 kg CO_2 emissions avoided and payback period of 4.6 years is analysed. Sensitivity analysis based on design parameters such as collector area, tilt angle and tank volume is performed to highlight the important design

Abbreviations A_c, Collector Area; β, Collector tilt; G_{dir}, direct beam solar irradiance; G_{diff}, diffused solar radiation; T_{cm}, average collector temperature; T_A, Ambient temperature; F_{IAM}, Incident angle modifier; *k*, Heat transfer coefficient.; *P*, Energy absorbed by the collector; η, System efficiency; GHG, Greenhouse Gas; TCE, Tonne Of Coal Equivalent; GB, Gilgit-Baltistan; LPG, Liquefied Petroleum Gas; ETC, Evacuated Tube Collector; SWH, Solar Water Heating; FPC, Flat Plate Collector; UnGC, Unglazed Collector; NASA, National Aeronautics and Space Agency; MW, MegaWatt; HTF, Heat Transfer Fluid; DHW, Domestic Hot Water; S.F, Solar Fraction; NPV, Net Present Value; IRR, Internal rate of return

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considerations. Based on the techno-economic analysis, it is concluded that ETC is the most feasible SWH system for the northern regions of Pakistan.

1. Introduction

Globally, the world is moving towards renewable and green energy sources due to the decline in energy costs, improving energy efficiency, depletion of conventional energy sources and polluting nature of fossil fuels [1,2]. Renewable energy sources have the potential to reduce greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) $46405 \times 10^3 t$ by end of 2022 [3,4]. Energy is the basic need of life and the cold climatic regions often have much higher energy demand than regions with warmer climatic conditions especially during in the winters. It is reported that in Canada, space heating utilises the major chunk of energy due to the harsh cold climatic conditions and an average household annual energy demand used for the heating purpose is much higher compared to power energy [5]. According to the National Science and Engineering Research Centre, the commercial buildings energy consumption in Canada is 53% of total national electricity consumption and contributed to 28% of GHG emissions. Similarly, in Northern China, space heating consumed 201 million TCE (Tonne of coal equivalent) in 2017 which consequently contributing to huge chunk of GHG emissions [6]. The continuous growth of heating demand and related energy consumption is becoming a prominent issue, especially in the colder regions. To alleviate this problem, many countries are shifting towards renewable energy sources to fulfil the basic heating demands [1,7]. Solar energy is the best source to fulfil the heating demands because of its low cost, simple structure and availability [8,9]. Recently, China and other developing countries have been utilizing solar energy for heating purpose at larger scale [10–12].

The tourism sector is the fastest-growing sector globally where tourism activities are increasing by 3% to 4.5% annually. This sector contributes 10.2% of the world GDP [13,14]. In Pakistan Gilgit-Baltistan (GB) is one of the favourite destinations of many tourists all over the world due to its utmost beauty and other famous historical and cultural heritage [15,16]. GB is located in the cold climate zone where locals and tourists face harsh climatic swings in most months of the year. Millions of foreign and local tourists visit every year GB for tourism. Attractions like Karakorum range mountains and other tourist spots entice tourists to visit these colder regions [17]. In the last decade, the number of local and foreign tourists have been increasing at an exponential rate [18]. Tourism is also creating a negative impact on the ecosystem of the GB and other northern parts of Pakistan [19]. Locals and tourists use conventional sources like wood and liquefied petroleum gas (LPG) for heating purposes. Especially most populated cities like Gilgit and Skardu mostly used LPG for heating purposes. This development has shifted the focus of the Government of Pakistan towards ecotourism development in the region [20–22]. Owing to insufficient resources of electricity in GB, the people of the area use wood and other fossil fuels to meet the heating demands. Burning the wood for heating purposes is not only creating serious health issues but also causing serious environmental issues due to deforestation in the region [23]. The significant increase in deforestation from the year 2000 to 2010 is about 75000 ha to 95000 ha in the northern part of Pakistan mainly due to excessive use of wood for heating purposes [24].

The NASA data and Pakistan Metrological Department reports show that this region has a good profile of solar radiation that can be efficiently utilised for heating purposes especially water heating [25]. Solar Water Heating (SWH) system is used for heating the water while using solar energy [26,27]. In the last few years, SWH technology has been using for various domestic and industrial applications [28,29]. SWH systems can operate independently or as a hybrid with electric or gas heating sources. Different types of SWH systems are used according to the locations, altitudes and weather conditions [30]. Among these, the evacuated tube and flat plate SWH systems are commonly used [31]. Previously few studies carried out on the effectiveness of the SWH systems and their contribution to sustainable tourism [32–34] and it is missing for the northern part of Pakistan especially the populated tourist area of GB. On the other side of the border in Ladakh, India is installing a 4 GW (GW) solar PV plant due to the excellent potential of global solar radiation. Ladakh has almost the same geographical and climatic conditions as the GB [35,36]. Ladakh is located in the north of India that has an altitude of 12,000 ft [37,38]. Countries like Germany, Sweden and Denmark have been using solar energy heating purposes especially in tourist areas [39]. SWH systems are also widely used heating systems in northern China, which is a tourist area with a very cold climate, mostly for hot water supply [40]. At the high altitude, there is plenty of solar irradiances available due to a pollution-free environment especially in the Himalayan region (Northern part of Pakistan and India) [41,42]. According to recent research, very healthy solar radiation are available in the mountain region due to the clear environment that can be used to produce hot water and electricity [43]. By looking into solar energy availability and current energy circumstances in GB, it is requisite to study SWH systems techno-economic analysis for ecotourism and sustainable development in GB, Pakistan.

The purpose of the research is to examine the potential of solar energy in GB (Gilgit and Skardu) for solar water heating (SWH) purposes and analyse the effectiveness of the SWH system and its contribution to sustainable and environmentally friendly tourism. To assess the solar potential of the study areas, climatic data, tourist and energy data is collected from concerned departments of the GB. To investigate the feasibility of the SWH system at GB, the SWH system was modelled using T*SOL software for two different regions of the GB with diverse climatic conditions. Furthermore, three different solar collectors were investigated to compare the maximum thermal

Fig. 1 Map of Gilgit and Skardu City Pakistan.

efficiency and solar fraction achievable under the influence of the available solar irradiance. Based on simulation results, the most suitable solar collector for water heating purposes has been identified for both locations, followed by sensitivity analysis to highlight the impact of design parameters such as collector area, tank volume and collector tilt angle on the overall system performance. Economic analysis for the proposed SWH system has been performed to assess the system feasibility to promote ecotourism and sustainable development of the GB region.

2. Methodology

The targeted cities of this study are Gilgit and Skardu in the region of GB as presented in Fig. 1. The GB is located in the north of Pakistan. Gilgit located at 35°55′15″N & 74°18′30″E and the elevation of 1580 m and Skardu 35°17′25″N 75°38′40″E with an elevation of 2228 m. Skardu and Gilgit are two major cities of the GB region that hosts most of the tourists [44]. Weather and Climatic data of the Gilgit and Skardu regions are collected from Pakistan Metrological Department. Tourists and energy data has been acquired from the Tourism Department and Power Department of GB. From the available data, the solar potential of GB is analysed for this study. After that, based on the collected data, software evaluation work using T*SOL software is performed to investigate the feasibility of an SWH system in both cities.

2.1. Metrological data

To assess the potential of the SWH system for sustainable tourism in GB, the data has been acquired from relevant departments. According to the GB tourism department, about 2.0 million tourists visited the region in 2019 including foreign visitors around the globe. The number of domestic tourists was about 2.2 million and foreign tourists were 31,000 [45,46]. The monthly average climatic data of Gilgit and Skardu are tabulated in Fig. 2(a,b). Climatic data comparison relevant to the current study includes solar radiation, atmospheric pressure, ambient temperature and humidity.

Fig. 3 represents the daily sunshine hour of the Gilgit and Skardu region for the year 2019. It can be observed from Fig. 3 that more than 2000 sunshine hours are available in both cities on annual basis. On average, 7 to 8 sunshine hours per day are available during May-August, which are also the peak tourism months. The intensity of solar radiation is very high and profound due to the climatic conditions and landscape of this region [47].

According to the Water and Power Department of GB, the total energy demand of this region is 270 megawatts (MW). To meet this demand there are about 128 Hydro stations in GB and collectively hydropower generation capacity is 145.95 MW, rest of the energy demand is fulfilled by oil-based power generation systems. Due to the harsh climatic regions many of the hydro stations are shut down in the winter, due to the freezing of the rivers and canals. So, in this scenario the SWH system is requisite in this region to meet the heating energy demand otherwise people have to rely on wood and LPG burning for hot water system.

2.2. Solar water heating (SWH) system

2.2.1. Specification of SWH systems

Simulations were performed at both locations for three types of SWH systems that include evacuated tube collector (ETC), flat plate collector (FPC) and unglazed collector (UnGC) and results were compared. The simulations were performed using T*SOL software. T*SOL (Valentin Software GmbH) is used to develop, design and economic evaluation of SWH systems. T*SOL is simulation software that is used to analyse thermal solar systems, such as domestic heating. Previously T*SOL has been efficiently used for the assessment of SWH systems in different areas of the world [48].

In this study, a tourist resort is assumed as a standard case with a capacity of 4 people with average hot water consump-

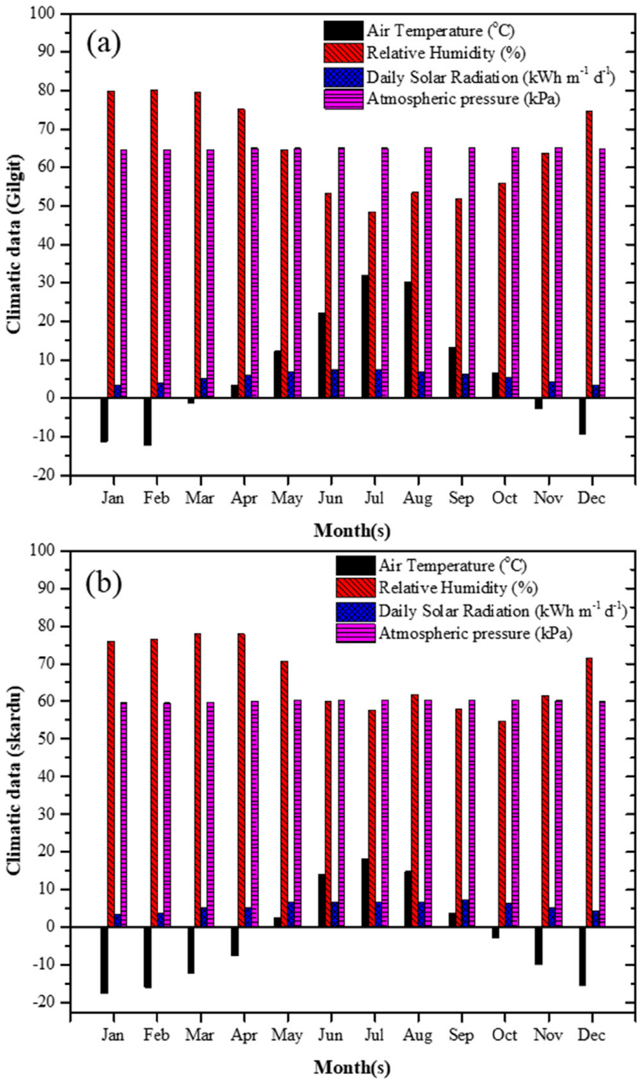

Fig. 2 Climatic data (a) Gilgit city (b) Skardu city (Source: Pakistan Metrological Department).

tion of 350 L/day. The energy consumption for a reported case is calculated on base load which is LPG and found 51.45 MJ/-day that is mostly used in these cities due to high population. To raise the temperature by 35 °C from ambient. Based on the heating value of the LPG source, the approx. energy consumption is 1.6 m^3/day subjected to ambient temperature. This energy demand is proposed to be substituted with solar which is a major potential renewable source in GB. To cater this energy demand a SWH system is requisite to be incorporated.

A SWH system is installed on the rooftop of the resort. Fig. 4 presents the schematic diagram of the SWH system consisting mainly of solar collector, storage tank, conventional boiler, pump and piping network. Table 1 presents the SWH system specifications, used as input to T*SOL model. The piping inside the resort is 5.0 m, outside is 1.0 m and 200 mm between the collectors. The thermal conductivity of insulation for these pipes 0.045 $W/(m.k)$. Auxiliary heating through LPG geyser/boiler is provided during the night, cloudy days

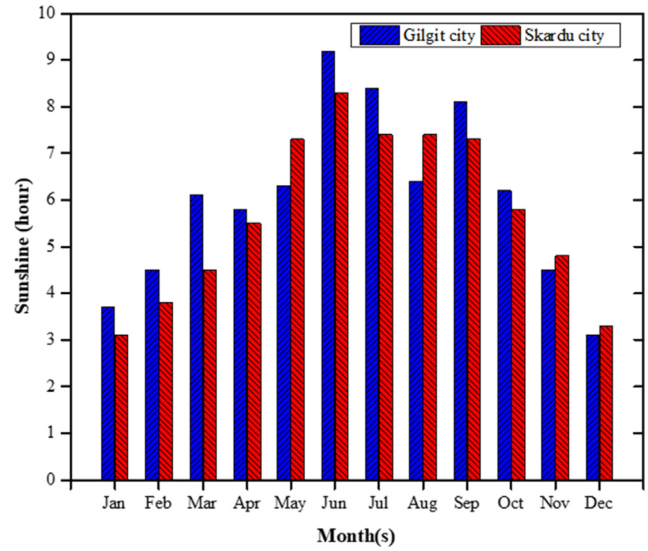

Fig. 3 Sunshine hour for Gilgit and Skardu (Source: Pakistan Metrological Department).

or non-availability of sufficient solar energy. Due to the harsh cold weather of Skardu, the operating time of the SWH system is throughout the year, however for Gilgit, there is no hot water demand during June, July, and August as per base load data.

2.2.2. Mathematical model

T*SOL® is designed for the simulation of solar systems, for example, detached and semi-detached homes and enables the immediate presentation of the respective solar system, including revenue and profitability forecasts, which provide significant design insights to planners, installers, energy consultants and architects.

a. Energy balance of solar thermal system:

T*SOL works on a thermal energy balance to calculate the status and temperature changes during the simulation period, by the numerical solution of a differential equation for the individual system components (Eq. (1)): Collector, collector loop, heat exchanger and water tank.

$$Temperature\ Difference = \frac{Total\ input\ and\ out\ energies}{Total\ of\ heat\ capacities} \quad (1)$$

For each of these components, the change in temperature is calculated with the above equation based on energy input and output and the heat capacity of the respective component.

b. Solar irradiation

Irradiation on the collector area (active solar surface) is calculated from the radiation strength (W/m^2) on the horizontal plane, while the height of the sun and the solar azimuth is determined based on the date, time, and latitude. Based on the height of the sun, the solar azimuth angle, the collector tilt

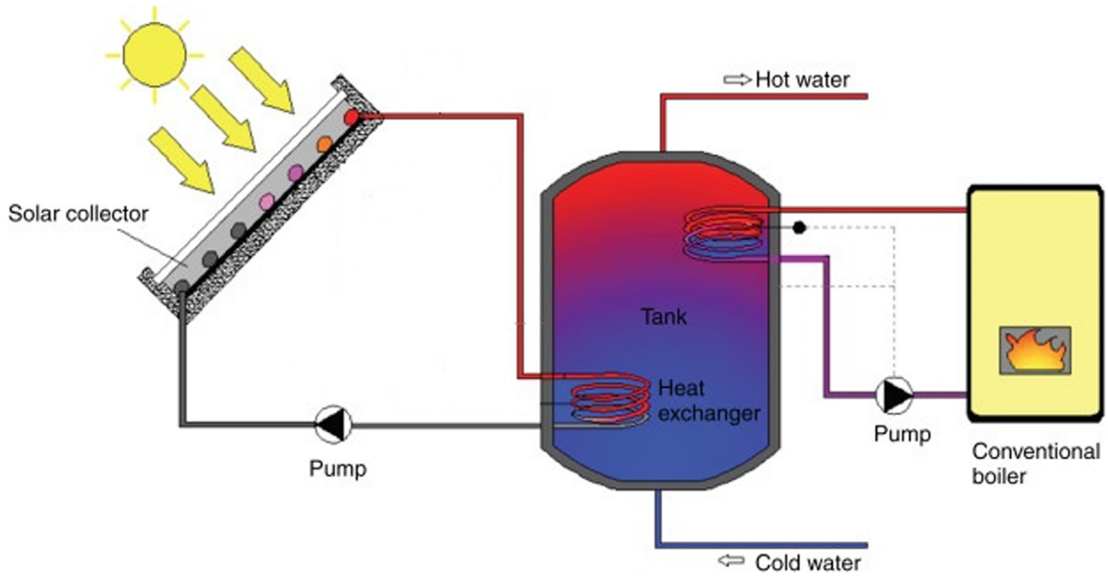

Fig. 4 Schematic diagram of SWH system.

Table 1 SWH system specifications.

Category	Specification
Installed collector power	4.0 kW_{th}
Number of solar collectors	4
Installed solar surface area (gross)	4 m^2
Collector tilt	45°
Collector Azimuth	0°
Water- Glycol mixture	40% Polypropylene Glycol
Volume Flow rate of collector	40L/h/ m^2
hot water consumption	350 L/day
Desired DHW temperature	50 °C
Desired temperature for storage tank	45 °C
Insulation thickness of storage tank	100 mm

Table 2 Heating value and emissions factors.

Fuel	Heating value	Emissions factor
Oil	36722 kJ/l	7.32748 g CO_2/kJ
Gas	41100 kJ/m^3	5.14355 g CO_2/kJ
Wood pellet	15490 kJ/kg	CO_2-neutral

angle, and the collector azimuth angle, the position of the sun relative to the collector surface is calculated.

c. Collector thermal model

The energy absorbed by the collector and output to the collector loop, heating losses are calculated by using Eq. (2):

$$P = G_{dir}.\eta_o.F_{IAM} + F_{IAM_{diff}}.G_{diff}.\eta_o - k_o.(T_{cm} - T_A) - k_q.(T_{cm} - T_A)^2 \quad (2)$$

Whereas P is the energy absorbed by collector, G_{dir} is direct beam solar irradiance and G_{diff} is dispersed solar radiation hitting the tilted surface, T_{cm} is average collector temperature, T_A is temperature of the air, F_{IAM} is incident angle modifier and k. is the heat transfer co-efficient.

d. CO_2 emissions saving

The CO_2 emissions saved by the solar system are calculated on the basis of primary energy/fuel saved by the solar system. Emissions factors by fuel type are used to calculate the CO_2 emissions of a heating system (Table 2). The following emissions factors are used in T*SOL®:

System efficiency and solar fraction

Collector loop efficiency and system efficiency is calculated using Eq. (3)–(4) [49].

$$Collector\ loop\ efficiency = \frac{Energy\ output\ from\ collector\ loop}{Energy\ irradiated\ on\ to\ the\ collector\ area}$$

$$System\ efficiency = \frac{Energy\ output\ from\ the\ solar\ system}{Energy\ irradiated\ on\ to\ the\ collector\ area}$$

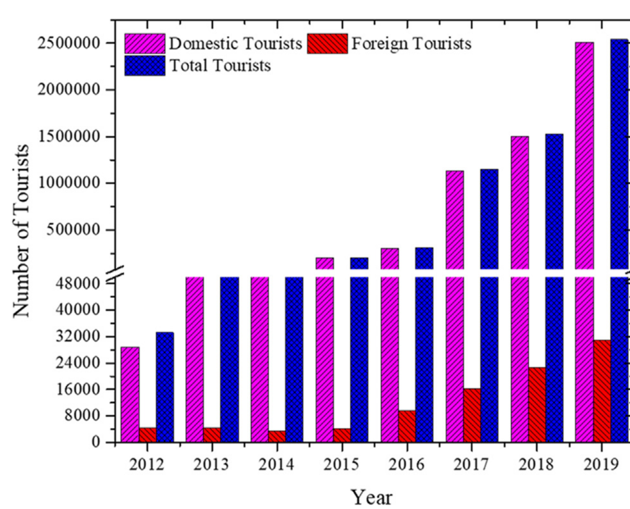

Fig. 5 Number of tourists visit in GB from 2012 to 2019.

The energy output by the solar system consists of the energy transferred from the solar storage tank as a result of water consumption.

The solar fraction (S.F) is the contribution of solar energy to the whole system's energy requirement, calculated using Eq. (5):

$$S.F = \frac{Energy\ suuplied\ to\ storage\ tank\ from\ solar\ system}{Energy\ supplied\ to\ storage\ tank\ from\ solar\ system + auxiliary\ system} \quad (5)$$

3. Results and discussion

3.1. Tourism impact and energy demand

The tourist activities from 2012 onwards 2019 is presented in Fig. 5. The information acquired from the tourism department of GB depicts that more than two million tourists visit GB in 2019, making it one of the most attractive destination for visitors all over the world [50]. The rate of tourists influx has been increasing exponentially in the last few years and multiples to come in the near future. This development has strengthened the economy of this region and generated revenue as well. However, the rapid increase in tourists in this region also has negative impacts from the energy point of view.

Most locals and tourists in mentioned cities use LPG for water heating that has serious environmental concerns [51]. Due to the recent tourism activities, the energy requirements in GB is increasing rapidly. The foreign tourist flow is also increasing exponentially which indicates a certain increment in the energy demand especially the hot water requirements for colder regions like Skardu.

3.1.1. Solar irradiance

The daily solar radiations of Gilgit and Skardu city is presented in Fig. 6. The daily solar radiation is 5.30 kWh/day in Pakistan and approximately 5.6 kWh/day in GB. The solar map of Pakistan represents that the major portion of Pakistan is obtaining solar radiation of 5–5.5 kWh/day. Therefore, the available solar energy in GB is plenty for the SWH application [52,53]. The average annual solar radiation is about 5.54 kWh/day, however, the maximum amount of radiation is received during September according to NASA sources [54]. The cold arid region of the country located at Gilgit and Skardu receives maximum radiation, that is approximately 7–7.5 kWh/day. At Skardu, the maximum radiation is obtained during June is 7.48 kWh/day. According to Pakistan Metrological Department, most of the days at GB are cloud-free. It is reported, as 300 clear sunny days in a year [55].

In December, January and February, solar irradiance is about 3 to 5 kWh/day. In the mid-winter season, the efficiency of solar collectors will be decreased due to low solar irradiance as depicted in Fig. 6. To overcome this problem, a hybrid heating system like gas and wood will be needed to provide sufficient heating because in winter the heating demand also increases due to the harsh cold weather [56]. In March, April, and November the radiation potential is normal and can meet the heating requirements. In summer, the availability of solar irradiance is very high and profound that can certainly meet all kinds of heating requirements. It is to be noted, some of the tourist points in the Skardu region will be requiring space heating also due to high altitude and cold weather throughout the year [56].

3.1.2. Sunshine hour

The monthly average sunshine hour of the Gilgit and Skardu region is presented in Fig. 7. GB has mostly sunny days throughout the year and also analysed the weather report for the last five years. It has been analysed from the data that there are three to four days cloudy, and the rest are clear. The longest day recorded in Gilgit is in July which is almost eleven hours and the longest day recorded in Skardu is twelve hours in June. Most of the place in GB has very clear and pleasant weather and receive good solar radiation. Especially in summer, the ambient temperature is about 22 °C but solar irradiance is more than 6 kWh/day. In summer there are more

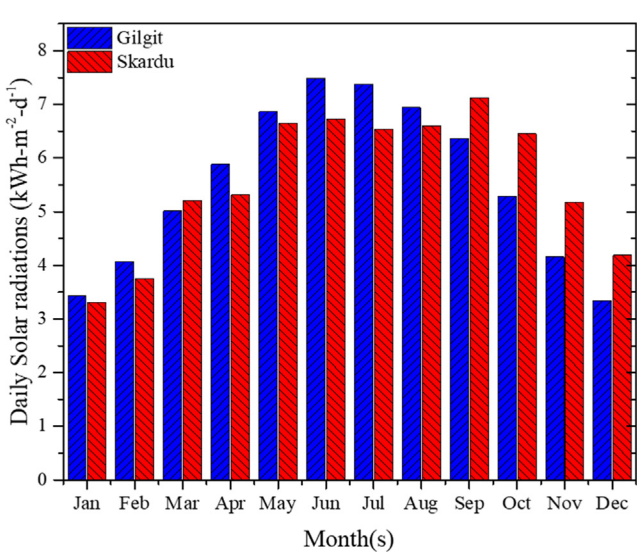

Fig. 6 Daily solar radiations (monthly average) for Gilgit and Skardu City.

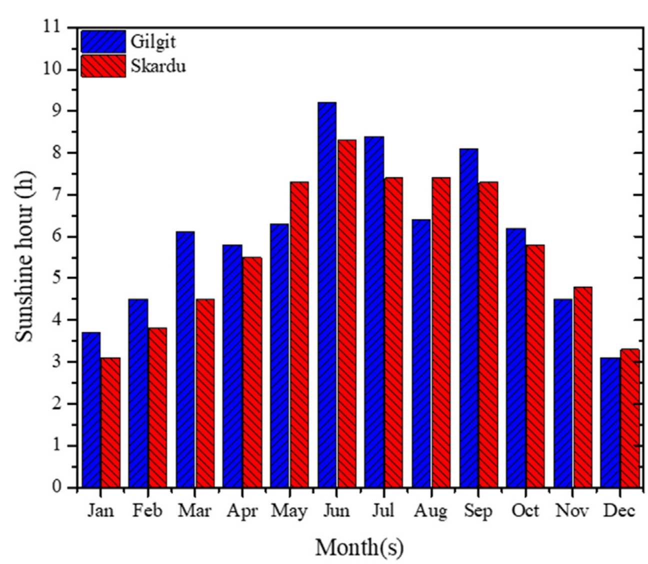

Fig. 7 Daily sunshine hour (monthly average) for Gilgit and Skardu City.

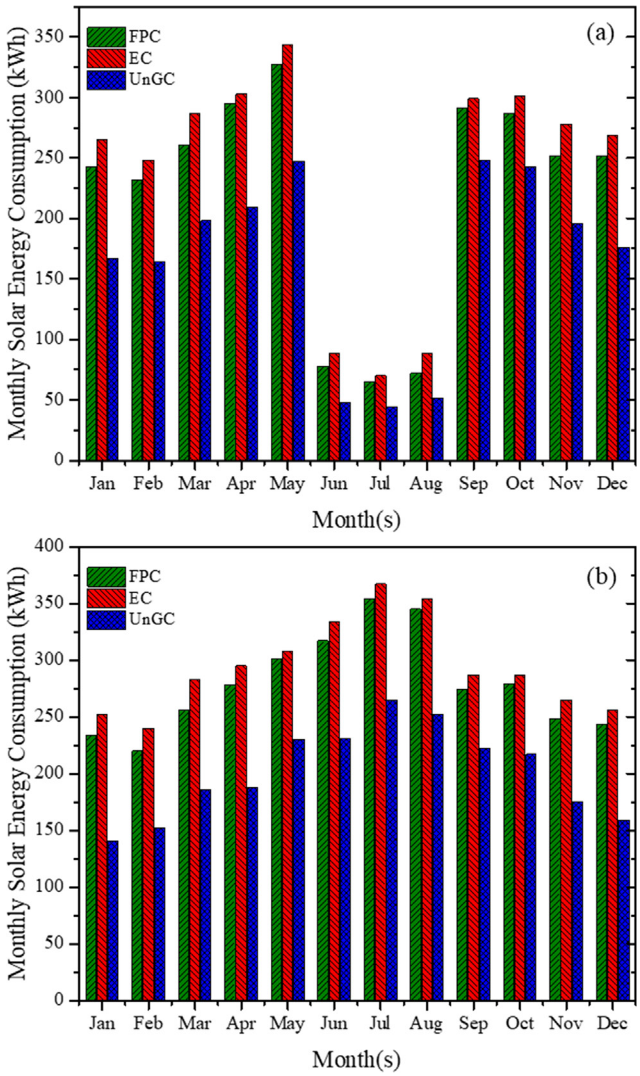

Fig. 8 Monthly solar energy consumption (a) Gilgit (b) Skardu

shining hours as compared to winter months. Fig. 7 reflect that winter has adequate sunny days for both cities. The tourist flow is heavy in summer as compared to winter, which also reflects the feasibility of sunshine for SWH systems in the region. For winter, the hybrid systems are considered more effective in Gilgit and Skardu.

3.2. Solar water heating (SWH) systems' analysis

After analysing the feasibility of the basic requirements, the need, solar irradiance and sunshine hour, the SWH systems were analysed. Three widely used solar collectors, FPC, ETC and UnGC as defined earlier were investigated for, monthly solar energy consumption, maximum collector temperature and overall efficiency and its suitability in Gilgit and Skardu city of GB.

3.2.1. Monthly solar energy consumption

Fig. 8(a-b) represents the solar energy consumptions of different collectors throughout the year. For the Gilgit region, solar consumption is low in June, July and August because the system is not in operation in those months. In these months, the weather of Gilgit is warm and does not need hot water. However, Skardu city, need hot water throughout the year therefore solar consumption of Skardu city is high in July that is about 350-kWh per month. In Skardu, solar energy consumption in June, July and August is maximum and sufficient for solar heating demands. For Gilgit, the highest consumption is in May which is about 330 kWh for FPC, 340 kWh for ETC, and 250 kWh for UnGC. The lowest consumption is in February during operation, that is about 230 kWh for FPC, 250 kWh for ETC, and 160 for UnGC respectively. For Skardu, the maximum solar consumption is in July that is about 350 kWh for FPC, 360 kWh for ETC, and 260 kWh for UnGC. In winter minimum solar consumption of Skardu is in February, that is near 220 kWh for FPC, 240 kWh for ETC and 150 for UnGC. The simulation results represent that the ETC has maximum solar consumption as compared to a FPC and UnGC. The solar radiation power of northern Pakistan is strong and highly intense that increases solar energy consumption [57]. Solar energy consumption in GB is high

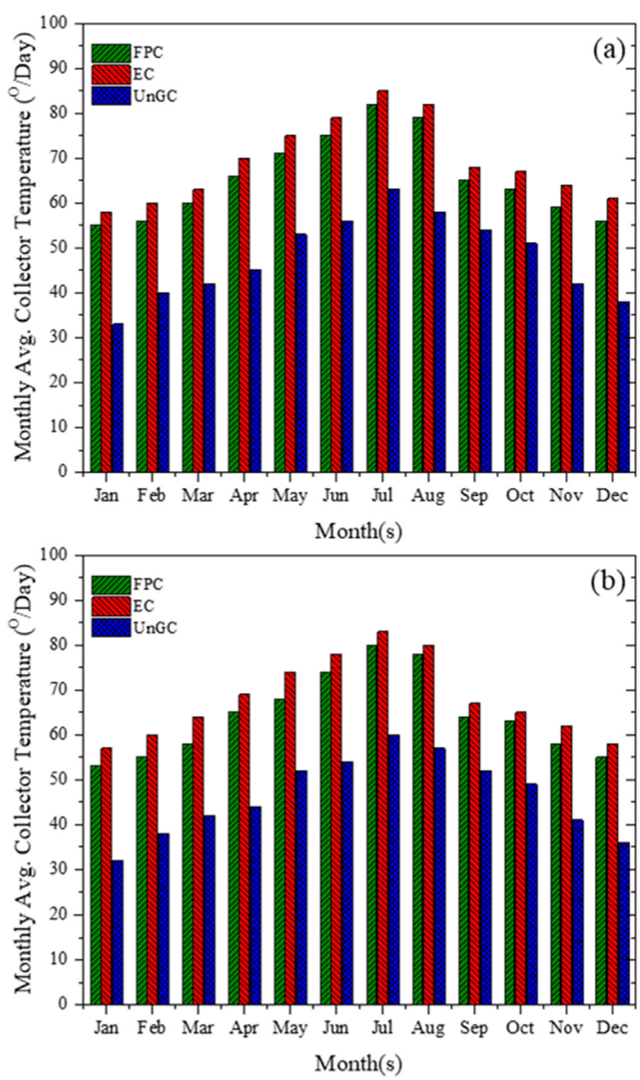

Fig. 9 Daily maximum collector temperature (monthly average) (a) Gilgit (b) Skardu.

as compared to plain areas of Pakistan due to a pollution-free and clean environment [58]. The solar energy consumption of ETC is high because this collector performs better in high altitude cold regions due to its technological suitability [59]. It also depicts that the performance of the ETC is better that suits the environmental conditions and geographical landscape of this region.

3.2.2. Daily maximum collector temperature (monthly average)

Collector temperature is the key factor for efficient solar heating systems. Fig. 9(a-b) represents the monthly average of daily maximum solar collector temperature for the Gilgit and Skardu regions. In the summer season, the collector receives maximum radiations because the days are longer and sunny, so collector temperature is high in the summer season as compared to the winter season. For Gilgit and Skardu region the maximum collector temperature reaches more than 80 °C in July and it is lowest in January which is about 50 °C for ETC and FPC. Fig. 9(a) represents the daily maximum collector temperature of different types of collectors include FPC, ETC, and UnGC. For the Gilgit region, the daily maximum collector temperature is highest in July which is 82 °C for FPC, 85 °C for ETC, and 63 °C for UnGC collector. The daily maximum collector temperature is lowest in January that is 55 °C for FPC, 58 °C for ETC, and 33 °C for UnGC.

For the Skardu region, the daily maximum collector temperature is also highest in July which is 80 °C for FPC, 83 °C for ETC, and 60 °C for UnGC respectively (Fig. 9(b). The daily maximum collector temperature is lowest in January which is 53 °C for FPC, 57 °C for ETC, and 32 °C for UnGC collector. Collector temperature depends on both intensity of radiations and ambient temperature [60]. The solar radiation potential of Gilgit and Skardu is almost equal but the ambient temperature is cooler in the Skardu region [61]. Therefore, the maximum collector temperature of Gilgit city is slightly higher as compared to Skardu city. From these results, it is observed that the ETC receives maximum collector temperature as compared to a FPC and UnGC [59]. It means that ETC is more efficient as compared to other collectors in this geographical landscape. ETC performs efficiently both in the winter and summer seasons due to its better output. So, ETC seems a suitable option to achieve the desire collector temperature for the solar heating system in this high-altitude cold region [62].

3.2.3. Overall performance of SWH systems

Simulations were performed for each FPC, ETC and UnGC to know their overall efficiency performance and results were analysed. Obtained simulation results are presented in Figs. 10-12. These results include solar fraction, solar contribution to hot water, CO_2 emissions reduction, and overall system

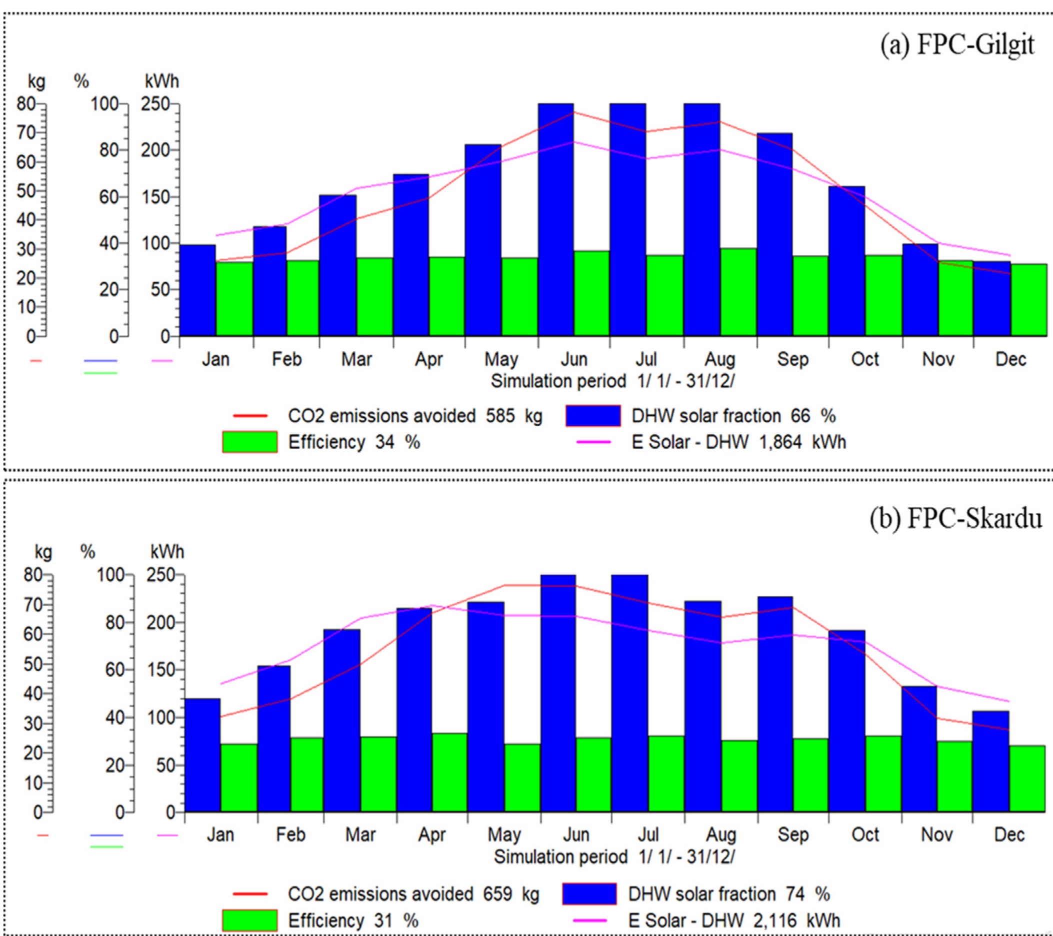

Fig. 10 T*SOL simulation results of FPC (a) Gilgit (b) Skardu.

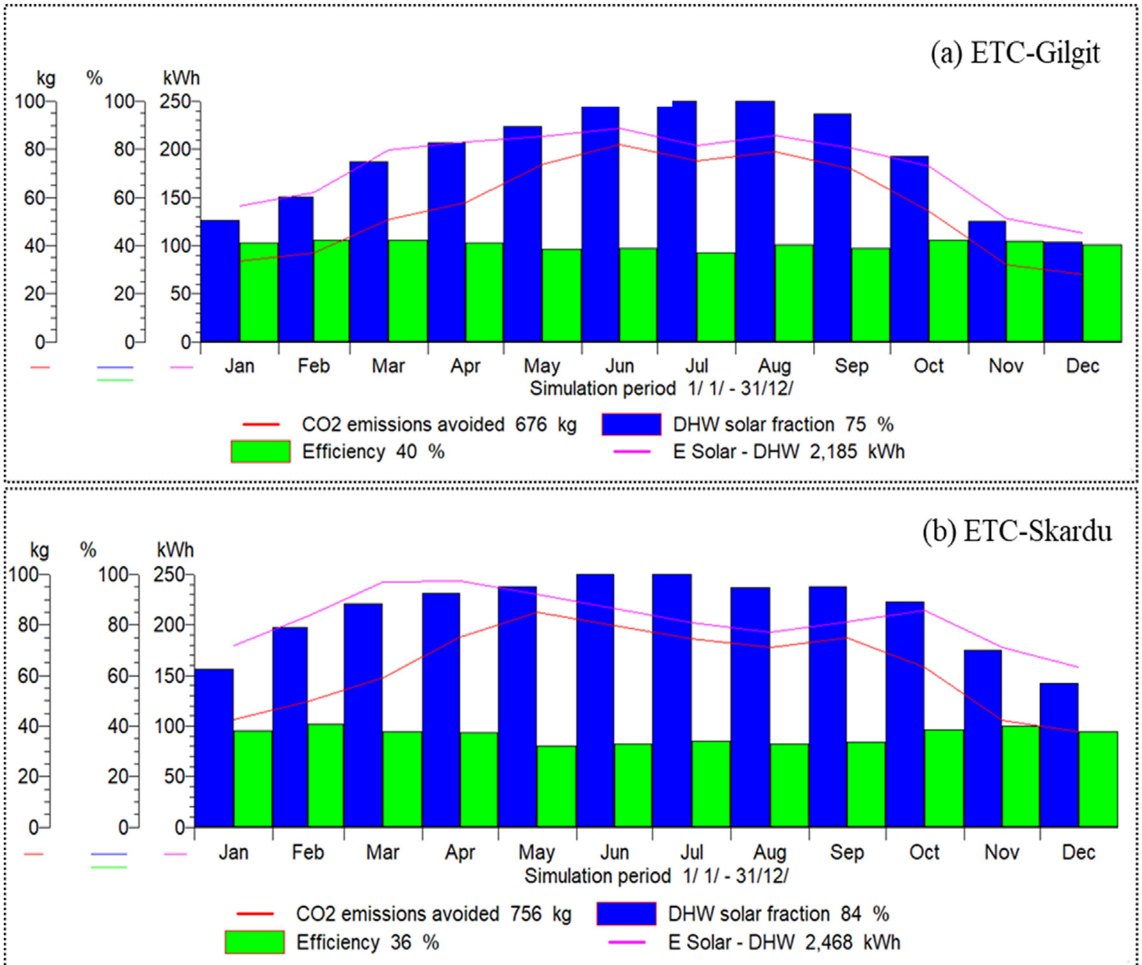

Fig. 11 T*SOL simulation results of ETC (a) Gilgit (b) Skardu.

efficiency of the SWH system. Fig. 10(a-b) represents the simulation results of the FPC. The solar fraction is about 66% for Gilgit and 74% for Skardu throughout the year. The yearly solar contribution for Gilgit is 1864 kWh while 2116 kWh is recorded for Skardu. Total CO_2 emissions reduced for the Gilgit region are 0.644 ton while the Skardu region has 0.72 ton for the whole year. The system efficiency of FPC for Gilgit is 34 % however it is recorded 31% for Skardu.

The simulation results of ETC for Gilgit and Skardu is presented in Fig. 11(a-b). The average solar fraction of the ETC for Gilgit city is nearly 75% while it is 84% for Skardu. Overall solar contribution to hot water for Gilgit city is 2185 kWh while Skardu city reflects 2468 kWh. Total CO_2 emissions prevented for the Gilgit region are 0.74 ton and the Skardu region is 0.83 ton for the whole year. The system efficiency of ETC for Gilgit is 40% whereas it is 36% for Skardu.

Fig. 12(a-b) represents the simulation results of UnGC for Gilgit and Skardu regions. The average solar fraction of the UnGC for the Gilgit region is 38% while 42% is for Skardu region. Solar contribution to hot water for Gilgit city is 967 kWh and Skardu city shows 1115 kWh for the whole year. The total CO_2 emissions reduced for Gilgit city are recorded 0.35 ton while it is 0.40 ton for Skardu city. The overall system efficiency of the heating system is 17.8% for Gilgit and 16.3% for Skardu city respectively.

The solar fraction of the Skardu city is higher than the Gilgit city because the solar heating system is not in operation during June, July and August for the Gilgit city. ETC has the highest solar fraction as compared to FPC and UnGC in both cities because the heat loss coefficient in ETC is low as compared to FPC and UnGC. Solar contribution is also high in Skardu city because this region has high solar energy consumption as compared to Gilgit City. Due to the high solar fraction, the solar contribution of ETC is also highest in GB [63].

The CO_2 emissions reduced by the SWH system in the Skardu region are slightly higher than in Gilgit city due to the high contribution of solar energy. System efficiency means the overall efficiency of the SWH system which considers all types of losses include thermal losses and piping losses [63]. The overall system efficiency of Gilgit City is slightly higher than the Skardu city because the maximum collector temperature of Gilgit city is superior to the Skardu city [64]. Table 3 shows the comparison of solar fraction, efficiency and CO_2 emissions prevented for three different collectors at Gilgit and Skardu cities.

From these results, it is observed that Gilgit and Skardu regions are feasible for the deployment of the SWH systems. The overall efficiency of both Gilgit and Skardu city is appreciable for ETC that FPC and UnGC. The ETC perform better

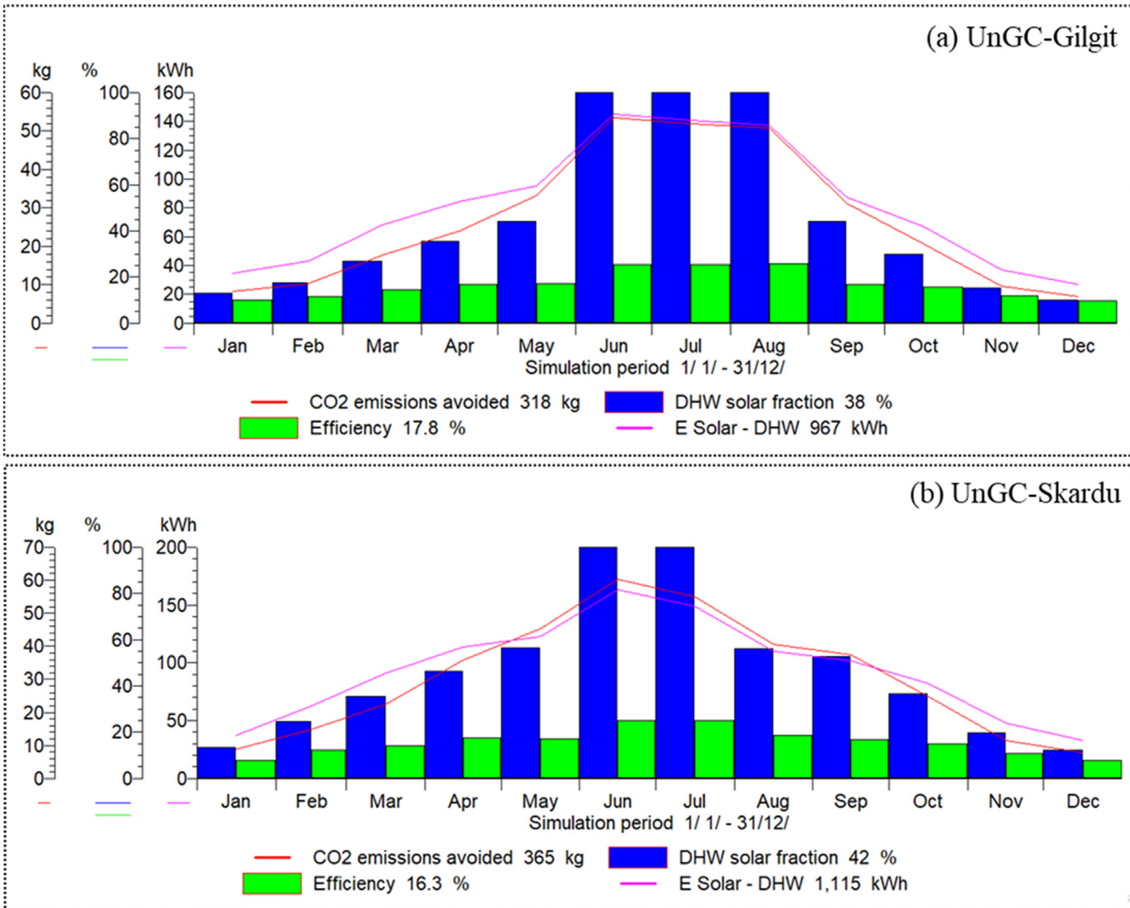

Fig. 12 T*SOL simulation results of unglazed collectors (UnGC) (a) Gilgit (b) Skardu.

Table 3 performance comparison for three different collectors at Gilgit and Skardu cities.

Collector	Gilgit city			Skardu city		
	S.F(%)	Efficiency(%)	CO_2 emissions avoided	S.F (%)	Efficiency(%)	CO_2 emissions avoided
FPC	66 %	34 %	585 kg	74 %	31 %	659 kg
ETC	75 %	40 %	676 kg	84 %	36 %	756 kg
UnGC	38 %	17.8 %	318 kg	42 %	16.3 %	365 kg

Table 4 Financial parameters for ETC system in GB-Pakistan

Project life span	20 Years
Current inflation rate	9%
ETC cost	44,150 PKR/collector
System installation cost (Labour and piping cost)	18,400 PKR
Loan instalments	Nil
Electricity cost in GB-Pakistan	7 PKR/kWh
Natural gas price	82 PKR/m^3

in cold climate areas because it has minimum thermal losses. It is reported that ETC has a high outlet temperature with reduced dispersion of heat as compared to FPC and UnGC [59]. In terms of solar collectors, the ETC has a much higher solar fraction, CO_2 emissions reduction, and system efficiency. The final comparison clearly shows that ETC is the most suited collector for the cooler climate of GB because the overall system efficiency of ETC is about 40 %. The specifications and design of ETC are more suitable for cold climate regions. FPC and UnGC are more susceptible to ambient heat loss as compared to ETC [59,62].

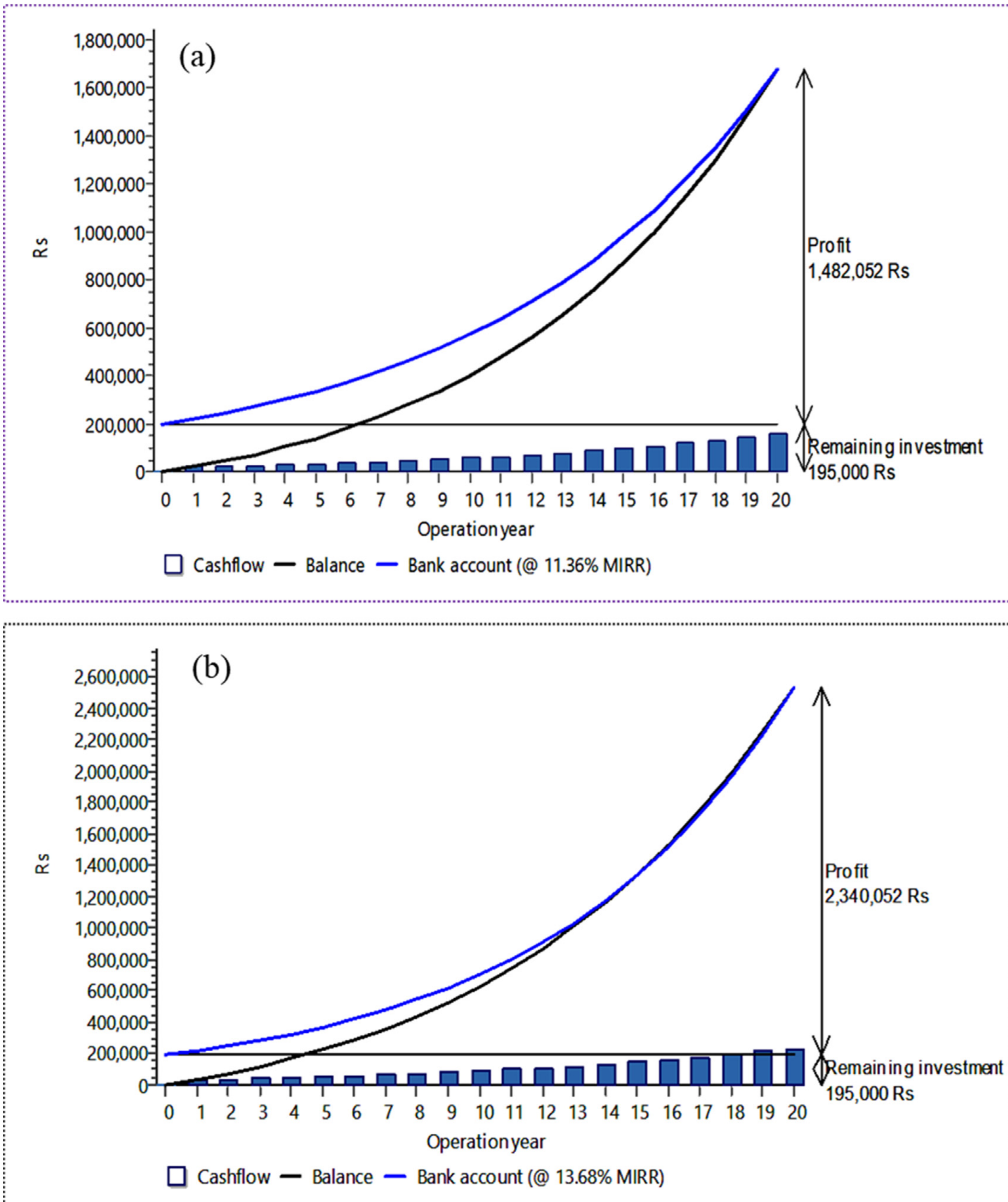

Fig. 13 Financial result for ETC system (a) Gilgit city (b) Skardu city.

Table 5 Financial results for SWH in Gilgit and Skardu Pakistan.

Parameters	Gilgit	Skardu
Payback period	6.6 years	4.6 years
Internal rate of return (IRR)	19.75%	27.41%
Amortization period	7.2 years	5 years
NPV	828,456 PKR	13,52,069 PKR
Profit surplus	14,82,052PKR	23,40,052 PKR

3.3. Financial analysis of SWH system

To analyse the SWH feasibility for both locations, financial analysis has been performed for the best suited ETC system, over the period of one year. For this purpose, the financial parameters for SWH in the GB region of Pakistan are considered are depicted in Table 4.

The simulation result for financial analysis at Gilgit is shown in Fig. 13(a). SWH based on ETC is able to achieve

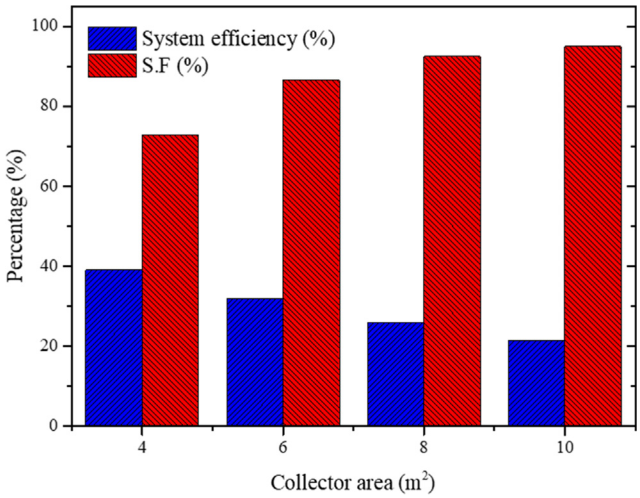

Fig. 14 Effect of collector area on system efficiency and S.F of ETC SHW system; volume of the tank = 350 L, title angle = 45°

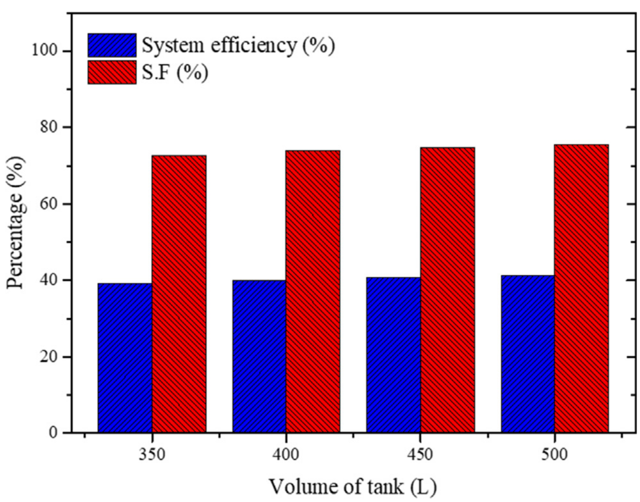

Fig. 15 Effect of tank volume on system efficiency and S.F of ETC SHW system: collector area = 4 m^2, title angle = 45°

breakeven within 6–7 years, afterwards giving a profit of 14,82,052 PKR (equivalent to 1817 US $) over the project life of 20 years. Furthermore, positive net present value (NPV) indicates that the SWH project is feasible at Gilgit as presented in Table 5.

Similarly, financial analysis for the SWH system in Skardu city is analysed, based on parameters listed in Table 4. Simulation results are shown in Fig. 13(b) indicate that SWH based on ETCs in Skardu city is able to achieve a breakeven period of 4–5 years, which is even less than for SWH system in Gilgit city as presented in Table 5. Furthermore, higher NPV and profit surplus proves the project feasibility in Skardu city.

3.4. Parametric analysis of SWH system

In order to highlight the impact of different parameters such as collector area, tank volume and collector tilt on the overall performance of SWH system, sensitivity analysis has been per-

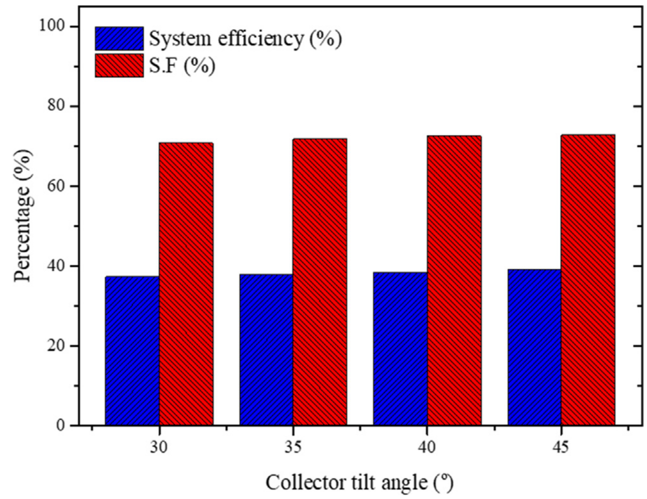

Fig. 16 Effect of collector tilt on system efficiency and S.F of ETC SHW system: volume of tank = 350 L, collector area = 4 m^2

formed for SWH using ETC in Gilgit city which is consequently applicable for Skardu city as well. Since ETC performance is better for both regions as can be seen in the SWH system analysis.

3.4.1. Effect of collector area

ETC SWH system is modelled with different collector areas of ETCs, and results are compared in terms of system efficiency and S.F (Fig. 14). It is observed that increasing the collector area while all other parameters such as water consumption, tank volume, desired temperature and collector tilt are kept constant, has a positive effect on S.F as it increases from 72.76% to 94.93%, while system efficiency drops from 39.14% to 21.38%. This can be explained by the larger surface area available for harvesting the solar energy, however overall efficiency decreases which could be due to system oversizing for the same hot water demand.

3.4.2. Effect of tank volume

ETC SWH system is modelled with different tank volumes from 350 L to 500 L, while all other parameters such as water consumption, collector area, desired temperature and collector tilt are kept constant. Simulation results indicate that by increasing the tank volume, both system efficiency and S.F increases from 39.14 % to 41.36% and 72.76% to 75.59%, respectively (Fig. 15). Since the large storage tank increases the availability of hot water after sunset or during cloudy days, however, it also increases the overall system cost.

3.4.3. Effect of collector tilt angle

SWH system is modelled with different collector tilt angle from 30° to 45° from horizontal and orientation due south, while all other parameters such as water consumption, collector area, desired temperature and tank volume are kept constant. Simulation results indicate that if collector tilt angle is decreased from 45° to 30°, S.F decreases from 72.76% to 70.75%, and system efficiency also declines from 39.14% to 37.29% (Fig. 16). Decreasing the collector tilt may decrease the solar irradiation incident on the collector surface, which in turn affect the S.F and overall efficiency.

4. Conclusions

The study analysed the techno-economic feasibility of SWH system for two locations Gilgit and Skardu in GB region. The hot water demand and weather data from various sources have been analysed to investigate the potential for SWH system in GB. SWH based on three different collectors ETC, FPC and UnGC is modelled in T*SOL software. Simulation results revealed that ETC system is able to achieve higher solar fraction (75 %) and efficiency (40 %) for Gilgit city and 84 % solar fraction, 36% efficiency for Skardu. Hence, the cold arid region of GB is the best place for solar energy harvesting as ETC showed a better overall performance for both cities with a significant reduction in CO_2 emissions. Furthermore, financial analysis for both region is analysed. The payback period for Gilgit is recorded as 6.6 years while Skardu city shows 4.6 years. The IRR for Gilgit is 19.75 while Skardu shows 27.41%. Finally, the sensitivity analysis highlights the impact of system parameters like collector area, tank volume and collector tilt angle on the overall system performance. Based on the performance analysis as well as economic assessment, it can be concluded that ETC SWH system is more feasible for Skardu city due to the cold climatic conditions and hence the requirement of hot water throughout the year. Overall, SWH system is an economical and clean energy source that can provide better facilities for tourists, promote eco-friendly tourism in GB, and can be a sustainable alternative to the conventional non-renewable sources for such colder regions.

CRediT authorship contribution statement

Muhammad Naveed Arif: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Adeel Waqas:** Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – review & editing. **Faaz Ahmed Butt:** Formal analysis. **Mariam Mahmood:** Software, Validation, Writing – original draft. **Asif Hussain Khoja:** Data curation, Investigation, Supervision, Visualization, Writing – original draft. **Majid Ali:** Formal analysis, Visualization. **Kafait Ullah:** Project administration. **M.A. Mujtaba:** Validation. **M.A. Kalam:** Funding acquisition, 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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