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Economic Assessment of Industrial Solar Water Heating System

In the present work, solar water heating systems having nominal water usage of 24 cubic meters per day are considered. To identify the better option, both technologically and economically, a typical geographical location in Saudi Arabia, namely Abha, is considered. Internal rate of return (IRR) values for the solar collectors with glazing are found to be higher as compared with that of the unglazed type. The glazed type collectors are found to be more efficient, provide greater savings in fuel consumption, and result in the reduction of greenhouse gas (GHG) emissions. The findings of this study can be used for locations with similar types of climatic conditions in any part of the world.

Keywords: *Solar Photovoltaics, Building Integrated Photovoltaic Systems, Energy, Renewable Energy, Cost of Energy.*

1. INTRODUCTION

Exponentially growing population and drastically increasing energy demands for meeting the residential and industrial loads have become matters of concern [1, 2]. These demands, both for direct electricity or heating loads, require fuel. Moreover, the power plants cannot be built to meet the pace of increasing energy demands [3–5]. Additionally, environmental concerns restrict the usage of fossil fuels for energy generation [6–8]. Hence, new, clean, and renewable energy sources, such as solar photovoltaic, solar thermal, wind, geothermal, tidal, biomass, etc. are being encouraged these days [9, 10].

Due to technological advancement, ease of use, competitive costs, and commercial acceptance, solar energy is being used widely for water heating and electricity generation. The global solar hot water and solar photovoltaic installed capacity trends are shown in Figure 1, Weblink1 [11].

The solar hot water installed capacity was 195 GWth in 2010 and increased to 223 GWth in 2011, which is an increase of 14.3%, REN21 [12]. In 2012, this capacity increased to 255 GWth, i.e., an increase of 14.3%, again compared to 2011. Solar hot water usage is increasing globally at a steady pace as observed from Figure 1. Solar PV generation is also increasing but at a slower pace. Usually, the solar-thermal conversion efficiency is about 70% but the solar photovoltaic electricity conversion system efficiency is about 17% [13]. Accordingly, as seen from the global installed capacities, solar water heating systems are popular due to their ease of maintenance and operation.

Many studies are reported in the literature on the performance of domestic water heater systems [14–21]. In a comprehensive review, Wang et al. [22] investigated solar water heating systems with phase change materials. Hazami et al. [23] showed that the flat plate and evacuated tube collectors provided about 8118 and 12032 kWh of thermal energy annually and the respective annual savings in electrical energy were about 1316 and 1459 kWh. The payback period was about 8 and 10 years. Allouhi et al. [24] presented the assessment of the feasibility of the SWH system under climatic conditions of Morocco.

Various studies related to heat transfer, friction factor, optimal design of solar water heater, building-integrated solar water heaters, and thermal performance of the solar water heating have been conducted in different regions by researchers such as [25–34].

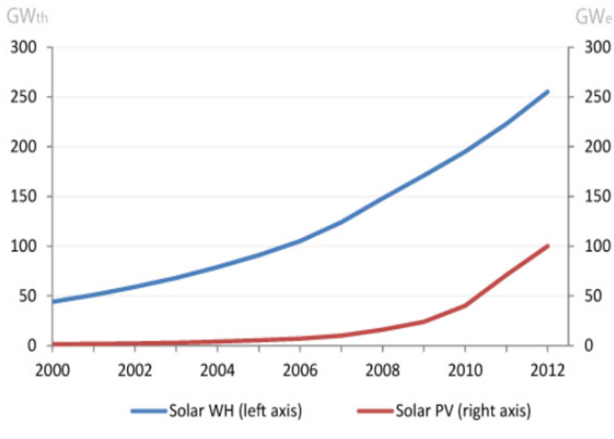

Figure 1. Global cumulative installed capacity growth of solar water heaters and solar photovoltaic systems

Keeping in mind the growing demand for hot water, conserving fossil fuel, and safeguarding our environment, an attempt is being made to promote the usage of solar energy-based hot water in relatively colder regions of Saudi Arabia and particularly the hill station of Abha in this case. Thus, a case study is presented here to verify and establish the economic and environmental feasibility of solar water heating systems.

The solar radiation intensity is 5.5 kWh/m2/d in this area which can be tapped for heating the water for industrial applications. This study aims at conducting

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the techno-economic feasibility of using glazed and unglazed flat plate solar collectors for heating the water. The study will propose the best possible option for the area under consideration and the areas having similar climatic conditions.

2. SOLAR WATER HEATING SYSTEM DESCRIPTION

Solar water heating systems are comprised of well-insulated storage tanks (normal water at ambient conditions and hot water), connecting pipes, and solar collectors (Figure 1). There are two types of solar water heating systems: active, which have circulating pumps and controls, and passive, which do not have pumps and controls.

Solar water storage tanks have an outlet and inlet connected to and from the collector. In the present study, glazed and unglazed flat plate types of solar collectors are used for comparative performance evaluation. Glazed flat-plate collectors are insulated, weatherproofed boxes that contain a dark absorber plate under one or more glass or plastic (polymer) covers. Unglazed flat-plate collectors have a dark absorber plate, made of metal or polymer, without a cover or enclosure.

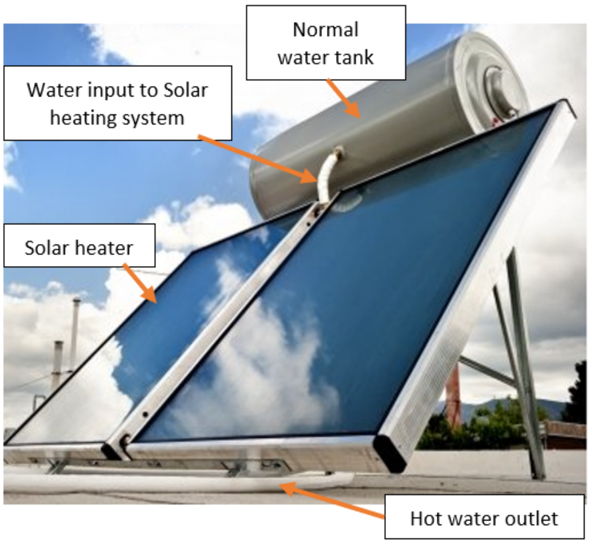

Figure 1. Major components of solar water heating systems

3. DATA AND SITE DESCRIPTION

Abha is a hill station situated at 2093 meters above the mean sea level in the South West of Saudi Arabia. The latitude and the longitude of the location are 18.2°N and 42.7°E, respectively. The main business lines of the area are tourism, hoteling, universities, and small-scale industries. For all of these applications, hot water is needed. Presently, electricity is mostly being used for heating the water in the residential sector while the industrial sector relies on natural gas-based water heating systems. The monthly mean meteorological parameters for Abha city are listed in Table 1.

The maximum monthly mean temperature (Temp) of 23.3°C is observed in June and the minimum monthly mean of 13.2°C in January. An increasing trend is observed in air temperature from January till June and then a decrease towards the end of the year. The temperature data showed a moderate climate of Abha city. The relative humidity (RH) varies between 39.1% in June to 70.2% in January as given in Table 1. The solar radiation (GSR) intensity is technically high and varies from 4.60 kWh/m2/d to 6.02 kWh/m2/d corresponding to February and October, respectively.

Table 1. Meteorological data for Abha city.

Month	Temp (°C)	RH (%)	GSR (kWh/m²/d)	PR (kPa)	WS (m/s)
Jan	13.2	70.2	4.74	79.8	3.8
Feb	14.6	67.8	4.60	79.8	4.4
Mar	16.5	64.4	5.37	79.7	4.2
Apr	18.3	60.8	5.62	79.7	3.3
May	21.1	50.6	5.89	79.8	2.7
Jun	23.3	39.1	6.01	79.6	2.7
Jul	23.2	44.4	5.52	79.5	3.0
Aug	22.6	51.7	5.30	79.6	2.8
Sep	21.9	38.9	5.73	79.7	2.9
Oct	18.5	43.6	6.02	79.9	2.5
Nov	15.6	61.0	5.50	79.9	2.4
Dec	13.8	67.1	4.81	79.9	3.0
Annual	18.6	54.9	5.43	79.7	3.1

The design and economic parameters, such as application and load type, daily hot water usage, operating days per week, inflation rate, debt ratio, project lifetime, hot water temperature, etc. for the proposed hot water system are summarized in Table 2. The inflation rate is taken as a sensitivity parameter varying from 2% to 5% with a 1% increment while the debt ratio is considered as zero. The required heating load for 24,000 L/d hot water requirement was found to be 238.7 MWh for both glazed and unglazed types of solar collectors. The solar collectors are considered as fixed with a slope angle of 20° and an azimuth surface angle of zero. The technical specifications, such as gross and aperture areas, collector's optical efficiency (Fr tau alpha), collector's thermal losses (Fr UL), and cost per collector of both the glazed and unglazed flat plate solar collectors are provided in Table 3. The balance of the plant parameters, such as fuel type, fuel seasonal efficiency, fuel cost, storage capacity, etc. is summarized in Table 4.

Table 2. Solar hot water heating system design parameters.

Description	Value	
Application	Hot water	
Load type	Industrial	
Inflation rate (%)	2 to 5	
Debt ratio (%)	0	
Project life (y)	20	
	Base case	Proposed case
Daily hot water use (L/d)	26,000	24,000
Days of operating/week	7	7
Temperature (°C)	60	55
Min supply temp (°C)	16.7	-
Max supply temp (°C)	20.2	-
Heating load (MWh)	238.7	-
Solar tracking mode	Fixed	-
Slope	20.0	-
Azimuth	0.0	-

4. RESULTS AND DISCUSSION

The simulation runs were made for a predefined duration of hot water usage during each month, as shown in Figure 2. In the proposed case, the duration of water usage varies from January till December with lower values during summertime and higher values in the winter period. The parameters defined in Tables 1 to 4 were used as input values to the model and the heat delivered, solar fraction, fuel consumption, greenhouse gases reduction, fuel cost, internal rate of return (IRR), equity payback period (EPBP), and simple payback period (SPBP) were obtained as outputs. The collector installed capacities and the inflation rates were used to study the effect of these parameters on IRR, SPBP, and EPBP. The output results are discussed in the sub-sections 3.1, 3.2, and 3.3.

Table 3. Solar collector specifications.

Description	Value	
Type	Glazed	Unglazed
Manufacturer	Thermo Dynamics	Acuquatherm Industries
Model	S32-P	Ecosun 16104
Collector area (m^2)	2.96	4.37
Collector aperture area (m^2)	2.76	4.37
τα coefficient Wind correction (s/m)	0.64 N.A.	0.82 0.07
Fr UL coefficient (W/m^2)/°C	4.65	15.76
Wind correction (J/m^2)/ °C	N.A.	2.28
Temp coefficient for UL (W/m2)/°C	0.0	N.A.
No. of collectors	50 to 100	34 to 68
Solar collector area (m^2)	148 to 296	148.5 to 297
Capacity (kW)	97.3 to 194.6	
Miscellaneous losses (%)	4	4
Cost/collector ($)	1,480	2,184

Table 4. System balance of plant and miscellaneous parameters.

Description	Glazed	Unglazed
Storage	Yes	Yes
Storage capacity /solar collector area (L/m^2)	75	75
Storage capacity (L)	10,425 to 20,850	11,136 to 22,272
Heat exchanger	No	No
Miscellaneous losses (%)	3	3
Pump power/solar collector area (W/m^2)	6.0	6.0
Electricity rate ($/kWh)	0.1	0.1
	Base case	Proposed case
Fuel type	Natural gas	Natural gas
Seasonal efficiency (%)	70	70
Annual fuel consumption (m^3)	22,158 to 14,297	29,176.1 to 24,420
Fuel rate ($/$m^3$)	0.40	0.40
Fuel cost ($)	8,863 to 5,719	11,671 to 9,768

4.1 Solar Collector Thermal Performance Analysis

In the present study, two types of flat plate solar collectors (glazed and unglazed) were considered to heat 24,000 liters of water daily for small-scale industries in the Abha region. The technical specifications of both types of solar collectors are summarized in Table 3. The gross area of a single glazed collector is 2.96 m2 while it is for the unglazed type and 4.37 m2. Accordingly, the number of collectors required to obtain almost the same total gross area to heat 24,000 liters of water per day, (an equivalent load of 238.7 MWh per day), were different as shown in Table 5. Since the number of the solar collectors was different, the storage capacities were slightly larger (5 to 7%) for the unglazed collectors as compared to the glazed collectors, as can be observed from the data listed in Table 5.

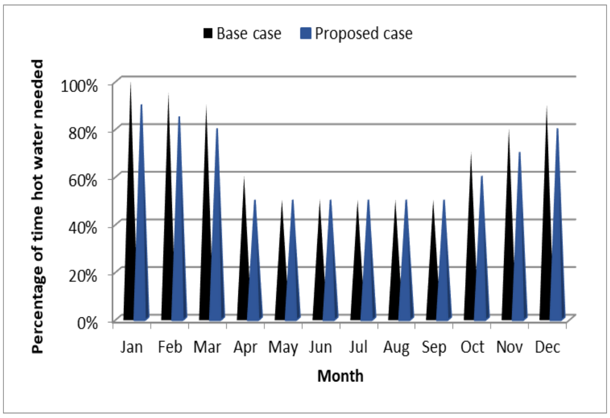

Figure 2. Percent duration of the time during which the hot water is used

The variation of the collector area (m^2) and the resulting system capacity load (kW) with many solar collectors for glazed and unglazed types are shown in Figures 3 and 4, respectively. It can be noticed that as the collector area increases, the capacity (kW) also increases releases but the rate of increase of the capacity slows down with a higher collector area. In other words, the gap between the area and the capacity buildup diverges with an increasing number of the solar collector means increasing the collector area, as seen from Figures 3 and 4.

However, the gap between the area and the capacity buildup was more in glazed collectors as compared to the unglazed collectors. Furthermore, larger capacities were achievable with unglazed as compared to the glazed collectors for the same collector area. For example, a capacity of 195 kW was achieved from a gross area of 295 m2 of the glazed collectors while it is almost 208 kW from the 297 m2 gross area of the unglazed collectors.

Table 5. Comparison of the monthly storage capacities resulting from the two types of solar collectors.

Glazed		Unglazed	
No. of Collector	Storage Capacity (L)	No. of Collector	Storage Capacity (L)
50	10,425	34	11,136
55	11,468	37	12,118
*60	12,510	41	13,429
65	13,553	44	14,411
70	14,595	48	15,721
75	15,638	51	16,704
80	16,680	54	17,686
85	17,723	58	18,997
90	18,765	61	19,979
95	19,808	65	21,289
100	20,850	68	22,272

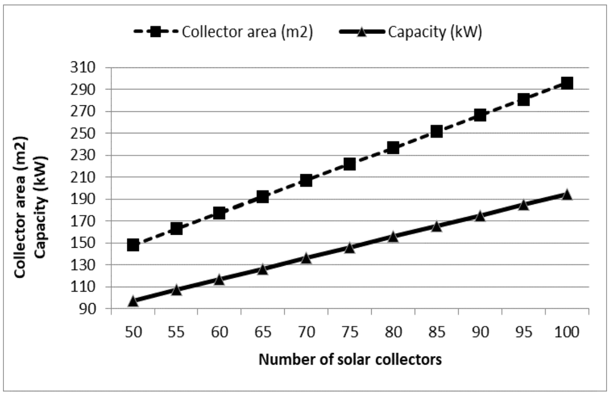

Figure 3. Variation of solar collector area and capacity with many glazed solar collectors.

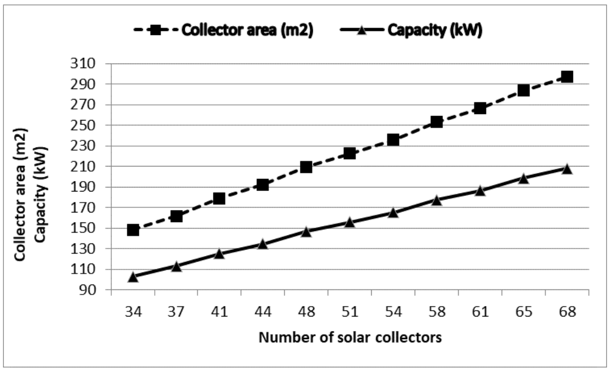

Figure 4. Variation of solar collector area and capacity with many unglazed solar collectors.

The useful clean and renewable heat delivered to the user and the solar fractions achieved from the proposed glazed and unglazed types of the solar collectors for specified load conations for the Abha area are shown in Figures 5 and 6, respectively. The Linear trends of renewable energy-based heat delivered (REHD) to the user and solar fraction achieved (SFA) versus the gross collector area of the glazed (GCGA) and unglazed (UGCGA) collectors were obtained and are given in equations 1 to 4, respectively.

$$REHD = 0.3869 * GCGA + 21.3 \quad R2 = 99.8\% \quad (1)$$

$$REHD = 0.2335 * UGCGA - 9.4673 \quad R2 = 99.8\% \quad (2)$$

$$SFA = 0.1615 * GCGA + 8.9545 \quad R2 = 99.6\% \quad (3)$$

$$SFA = 0.0956 * UGCGA - 3.3844 \quad R2 = 99.7\% \quad (4)$$

where REHD is the renewable energy-based heat delivered to the user, GCGA is the glazed collectors' gross area, UGCGA is the unglazed collectors' gross area, and SFA is the solar fraction achieved. It is evident from the linear trend in equations 1 and 2, that larger renewable energy-based heat could be achieved from the glazed flat plate collectors than the unglazed ones for the same gross area, as shown in Figure 7. Similarly, higher values of solar fractions were achievable with the glazed collectors as compared to the unglazed ones as can be understood from equations 3 and 4, respectively. The REHD values obtained from equations 1 and 2 glazed and unglazed solar collectors are compared in Figure 7. This figure also presents the trend of the differences in REHD values obtained from two types of solar collectors. Unglazed collectors were 157% less effective on average than glazed collectors. The effect of the size of the system indicated that the larger the area of the collector the lesser was the difference between the REHD values. Similarly, the effect of the gross area on the achievable solar fraction is depicted in Figure 8. The differences between the SFA values obtained from the glazed and unglazed-based solar collector hot water systems were found to decrease with the increasing gross area, as can be observed from Figure 8. On average, 150% fewer solar fractions were achievable from the unglazed collectors compared to the glazed ones but the fractions varied from 203% to 125% corresponding to the gross collector area of 150 m2 to 310 m2.

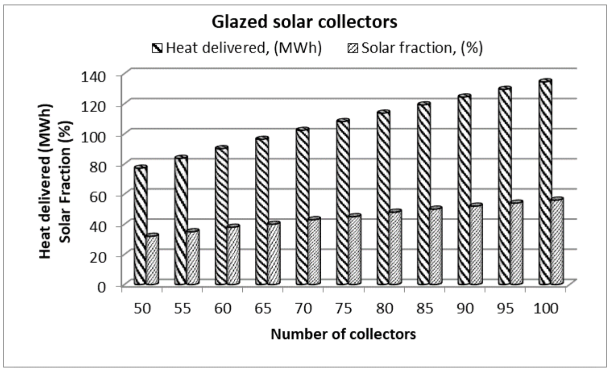

Figure 5. Variation of the heat delivered with glazed collectors and solar fraction achieved with collector's area.

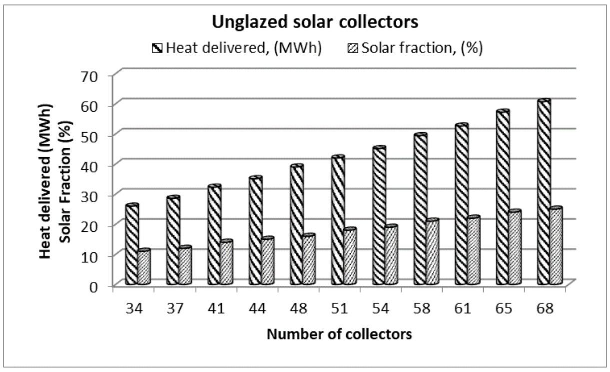

Figure 6. Variation of the heat delivered with unglazed solar collectors and solar fraction achieved with collector's area.

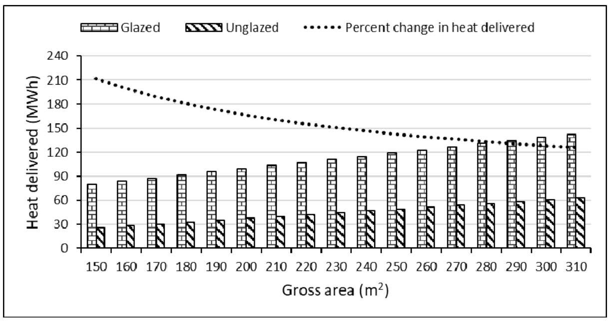

Figure 7. Comparison between REHD values from the glazed and unglazed systems.

4.2 Fuel Consumption and Greenhouse Gases Analysis

This subsection discusses the effect of the size of the solar water heating system on the annual fuel consumption and greenhouse gases reduction as a result of the solar energy usage for heating the water for industrial applications concerning climatic conditions of

Abha, which is a hill station in the southwest of Saudi Arabia. For the base case, i.e., in the absence of solar water heating or full dependence on natural gas-based water heating, a total of 44,030 m^3 of natural gas is required annually to meet the demand for hot water. The cost of the base case fuel consumption at the rate of 0.4 $\$/m^3$ was calculated as 17,612 \$. The annual fuel consumption, the fuel cost, and the reduction in GHG emissions for both glazed and unglazed types of solar collectors concerning the number of collectors (collector area) are provided in Table 6.

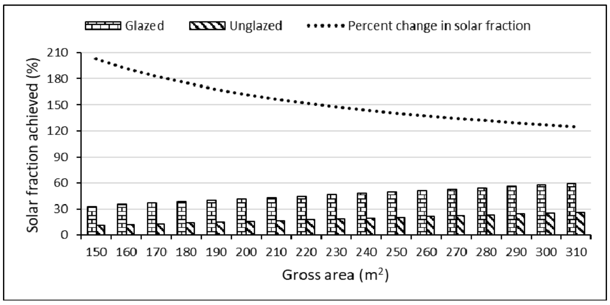

Figure 8. Comparison between the SFA values from the glazed and unglazed systems.

In the case of the glazed solar collector consisting of 50 collectors, the total fuel consumed was 22,158 m^3 while for almost the same area of the unglazed collector the fuel consumption was 29,176 m^3, as observed from the data given in Table 6. As compared to the base case, a net saving in fuel consumption was 21,872 and 14,854 m3 corresponding to the glazed and unglazed types of the solar collector based on the hot water systems, respectively. The corresponding net savings in terms of money were 8,749 \$ and 5,941 \$ compared to the base case cost of the fuel of 17,612 \$. For the largest size of water heater in the present case, the fuel savings for the glazed and unglazed solar collector systems were 29,733 m3 and 19,610 m^3 with respective cost savings of 11,893 \$ and 7,844 \$ as compared to the base case.

The reductions in fuel consumption and, consequently, the fuel cost from the base case are compared in Figures 9 and 10, respectively. It was evident from these illustrations that the savings in the fuel and the cost of the fuel were directly proportional to the installed capacity of the solar collectors. On average, a saving of 25,989 m3 and 17,125 m^3 for the glazed and unglazed collectors could be achieved for an average collector area of 222 m2. The corresponding fuel costs reductions of 10,396 \$ and 6,850 \$ were possible. The lifetime savings in the fuel consumption could reach a total of 519,780 m^3 for the glazed and 342,500 m^3 for the unglazed collectors. In addition to fuel reduction and cost savings, on average, 48 and 32 tons of GHG emissions can be avoided annually for the glazed and unglazed types of collectors, and if valid carbon trading certificate could be availed in exchange. Over the life span of the SWH of 222 m^2 capacity, a total of 960 and 640 tons of GHG could be replaced corresponding to the glazed and unglazed collectors with solar energy utilization.

4.3 Economic Performance Analysis

Based on the capital cost, the inflation rate, and the life of the proposed SWH systems, the internal rate of return (IRR), the simple payback period (SPBP), and equity payback period (EPBP) were analyzed and the sensitivity of the rate of inflation was studied. The variations of the IRR, SPBP and EPBP with the size of the SWH for 2% inflation are shown in Figures 11 and 12 for the glazed and unglazed types of the solar collectors, respectively. In the case of the glazed type of solar collectors, the IRR tends to decrease with increasing the SWH system size while the SPBP and EPBP tend to increase. This simply means that as the size of the system increases, more time is required for the payback investment amount. In the case of the unglazed type of solar collectors, the same trends were observed but in greater magnitudes, as observed from Figure 12.

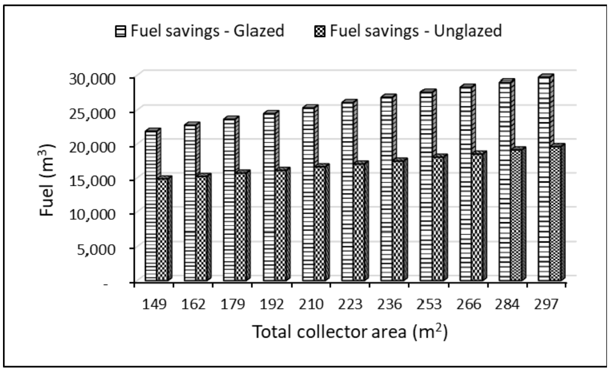

Figure 9. Fuel savings concerning the base consumption of 44,030 m3.

Table 6. Summary of the fuel savings and greenhouse gases reduction with the size of the system.

Glazed solar collectors				Unglazed solar collectors			
Number of Collectors	Annual Fuel Consumption (m^3)	Fuel Cost (\$)	GHG (tons)	Number of Collectors	Annual Fuel Consumption (m^3)	Fuel Cost (\$)	GHG (tons)
50	22,158	8,863	40.5	34	29,176	11,671	27.6
55	21,257	8,503	42.2	37	28,812	11,525	28.3
60	20,382	8,153	43.8	41	28,311	11,324	29.2
65	19,553	7,813	45.4	44	27,923	11,169	29.9
70	18,711	7,484	46.9	48	27,390	10,956	30.9
75	17,914	7,166	48.3	51	26,978	10,791	31.7
80	17,142	6,857	49.8	54	26,554	10,622	32.4
85	16,395	6,558	51.1	58	25,972	10,389	33.5
90	15,672	6,269	52.5	61	25,521	10,208	34.3
95	14,973	5,989	53.8	65	24,901	9,960	35.5
100	14,297	5,719	55.0	68	24,420	9,768	36.4

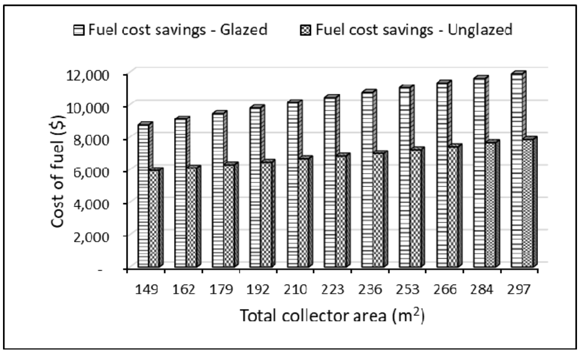

Figure 10. Fuel cost savings concerning base cost of the fuel of 17,612 $.

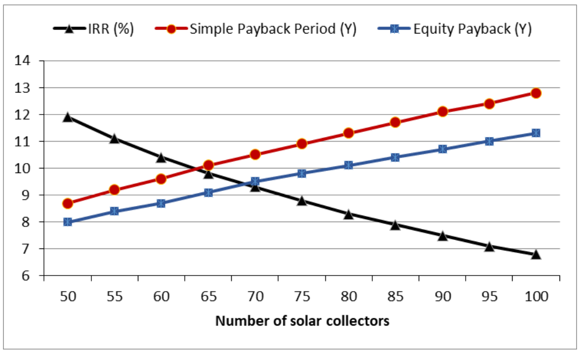

Figure 11. Variation of the IRR, SPBP, and EPBP with the glazed solar collector area for 2% inflation.

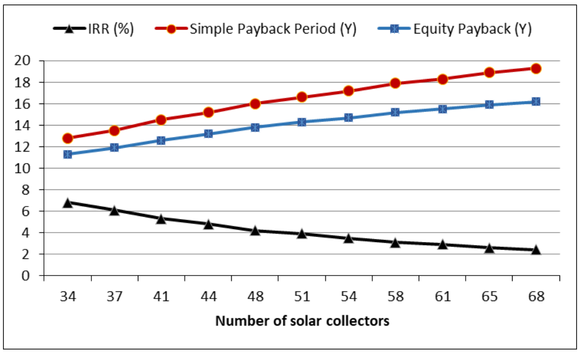

Figure 12. Variation of the IRR, SPBP, and EPBP with the unglazed solar collector area for 2% inflation.

The sensitivity of inflation rate on IRR and the equity payback periods were also analyzed and the effect of the rate of inflation on IRR for the glazed and unglazed type of collectors are shown in Figures 13 and 14; while that on the EPBP are presented in Figures 15 and 16, respectively. As the inflation rate increases, the IRR also increases for a particular size of the SWH system. For example, for a fixed size of 50 glazed collector systems, the IRR increases as the inflation rate go up from 2 to 5%, as shown in Figure 13. On the other hand, for a fixed inflation rate of 2%, for example, the IRR values decreased with increasing the size of the SWH system. Similar trends were noticed in the case of the unglazed type of solar collector based on the SWH systems but with relatively smaller values of IRR as compared to those for the glazed system.

For a fixed size of the SWH system, higher values of equity payback period were observed while lower values for the higher inflation rate, as shown in Figure 15 for the glazed type of solar collectors. For example, for 50 glazed types of collectors, the EPBP decreased from 8 to 7 years as the inflation rate increased from 2 to 5%. On the other hand, for a fixed inflation rate, the EPBP increased with increasing the size of the SWH system for both the glazed and unglazed types of solar collectors. However, higher EPBP values were observed in the case of the unglazed solar collectors as compared to the glazed ones, as seen in Figures 16 and 15, respectively.

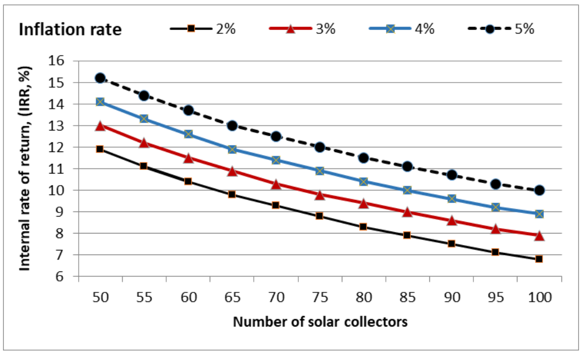

Figure 13. Variation of the IRR with the glazed solar collector area and rate of inflation.

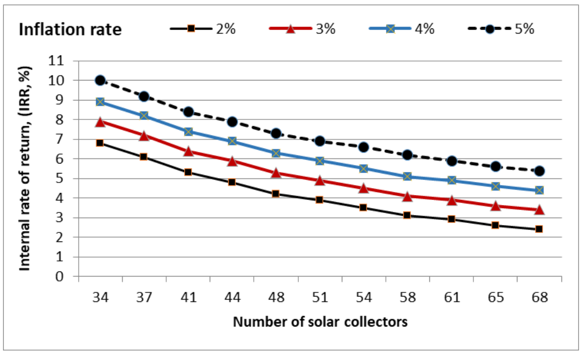

Figure 14. Variation of the IRR with the unglazed solar collector area and rate of inflation.

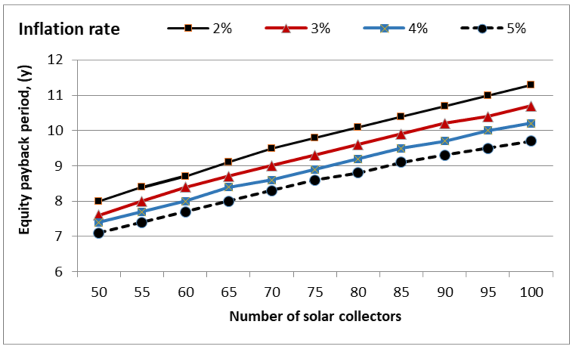

Figure 15. Variation of the EPBP with the glazed solar collector area and rate of inflation.

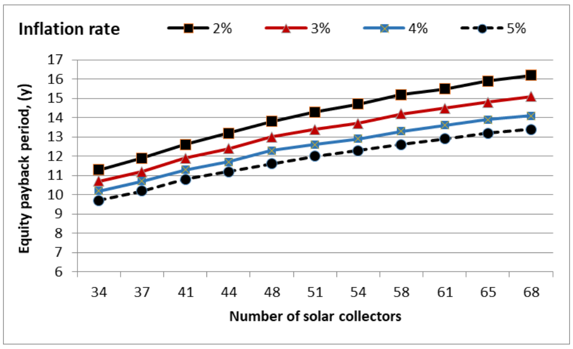

Figure 16. Variation of the EPBP with the unglazed solar collector area and rate of inflation.

5. CONCLUSIONS AND RECOMMENDATIONS

Solar energy-based hot water system with a nominal capacity of 24,000 liters per day of hot water supply for a small-scale industrial load was studied using glazed and unglazed types of collectors with a storage option for Abha, Saudi Arabia. The climatic conditions of the Abha area are moderate with an annual average temperature of 18.6°C and mean maximum of 23.3°C in June and a mean minimum of 13.2°C in January. The relative humidity varied from 39% in September to 70% in January with an annual average of 55%. Under these conditions, the system performance of the proposed system was carried out and the following points were found worthy to be highlighted:

With all possible combinations, the glazed solar collectors were found to be the most suitable for the Abha area and can be recommended for usage in areas having similar climatic conditions. For the same size of the solar collector areas, on average, almost 150% more renewable energy-based heat could be delivered to the user in terms of the hot water from the glazed collectors as compared to the unglazed collectors. Almost the same percentage difference was found for an achievable solar fraction. However, these differences in the heat delivered and the solar fraction achieved were found to be decreasing with increasing the solar collector gross area.

A total of 21,872 and 14,854 m^3 of fuel could be conserved annually corresponding to the glazed and unglazed types of the solar collector-based SWH compared to the base case with fuel consumption of 44,030 m3. The corresponding net cost savings were found to be 8,749 $ and 5,941$ compared to the base case cost of fuel of 17,612$. For the largest size of water heater in the present case, the fuel savings for the glazed and unglazed solar collector systems were 29,733 m^3 and 19,610 m^3 with respective to cost savings of 11,893 $ and 7,844 $ as compared to the base case. The IRR values were found to be decreasing with increasing the capacity of the SWH system. The IRR values increased with the increasing rate of inflation but the EPBP values decreased.

Last but not the least, the outcome of the presented work will be very useful for small-scale industries at a location having similar type of climatic conditions.

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ПРОЦЕНА ЕКОНОМИЧНОСТИ ИНДУСТРИЈСКОГ СИСТЕМА ЗА СОЛАРНО ГРЕЈАЊЕ ВОДЕ

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У овом раду се разматрају соларни системи за грејање воде са номиналном потрошњом воде од 24 кубна метра дневно. Да би се идентификовала боља опција, и технолошки и економски, посматрана је типична географска локација у Саудијској Арабији, односно Абха. Утврђено је да су вредности унут–рашње стопе поврата (УСП) за соларне колекторе са застакљењем веће у поређењу са незастакљеним колекторима. Застакљени колектори су ефикаснији, обезбеђују већу уштеду у потрошњи горива и резултирају смањењем емисије гасова стаклене баште (ЕГСБ). Налази ове студије могу се користити за локације са сличним типом климатских услова у било ком делу света.