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# Feasibility of Using Evacuated Tube Solar Water Heaters in Saudi Arabia

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**ABSTRACT**

*Electrical energy consumption in residential buildings increases rapidly in Saudi Arabia. Nearly 11% of residential energy consumed is due to the use of electricity for water heating. The purpose of this work is to investigate the performance of using the evacuated tube solar water heating system in residential buildings. Six locations in different climatic regions over Saudi Arabia have been selected for the investigation using measured data of weather and solar radiation. The technical performance and the economic feasibility of using solar water heating system in the selected sites have been investigated using* RET Screen *program through determining the delivered heat, solar fraction, the reduction in CO2 emissions, the savings in energy and cost, payback time, net present value and the benefit to cost ratio. The study with current conditions showed that there is a promising feasibility of using evacuated tube solar water heating system with heat pipe in Saudi Arabia, especially resulting from the encouraging payback time of less than 4 years for all investigated locations.*

**Keywords:** Solar Water Heater, RET Screen, heat pipe, Evacuated Tube, GHG emissions, Economic Feasibility

**Abbreviations**

| | | | | | |
|---|---|---|---|---|---|
| (B-C) ratio | - | *Benefit-Cost ratio* | LCS | - | *Life cycle saving* |
| BOS | - | *Balance of System* | NPV | - | *Net Present Value* |
| DWHR | - | *Drain water heat recovery* | SAMA | - | *Saudi Arabian Monetary Agency* |
| GHI | - | *Global Horizontal Irradiance* | SDWH | - | *Solar domestic water heater* |
| GHG | - | *Greenhouse gas* | SWH | - | *Solar water heating* |

K A CARE - *King Abdullah City for Atomic and Renewable Energy*
RRMM - *Renewable Resource Monitoring and Mapping*

## INTRODUCTION

The consumptions of electricity in residential buildings has increased rapidly in Saudi Arabia, mainly due to low energy prices, absence of energy conservation measures and growing population. The growth demand of electricity consumption in Saudi Arabia is 3-10% annually in the last 20 years [1]. Residential buildings consume a considerable amount of conventional energy that directly has a negative impact on the environment. In fact, this leads to significant greenhouse gas emissions. The share of residential electricity consumption in Saudi Arabia is about 50% of the total electricity consumption, while the world average 27% [2-3]. The need for domestic hot water represents a significant proportion of domestic energy consumption, which is nearly 11% of the total electricity consumption because all residential houses in Saudi Arabia use electricity to heat their water [4]. So, Saudi Arabia government should start several campaigns in order to promote energy efficiency and the use of renewable energy sources, especially solar energy.

Solar water heating (SWH) as one of the solar energy applications is one of the most developed, easiest ways and commercialized technology worldwide. Solar water heaters can be characterized as active system or passive system. An active system uses an electric pump to circulate the heat-transfer fluid, while passive system moves potable water or the heat-transfer fluid through the system without pump. Solar water heaters are also characterized as open-loop system (direct) or closed-loop system (indirect). An open-loop system circulates potable water through the collector, while the closed-loop system uses the heat-transfer fluid to transfer the heat to potable water via the heat exchanger.

In general, solar water heaters consist of two main parts: collectors and storage tanks. Collectors are three types: flat-plate collectors, concentrating collectors, and evacuated tube collectors. Flat plate collector, is an insulated, weather-proofed box containing a dark absorber plate under one or more transparent or translucent covers. The absorber plate contains built-in pipes to carry potable water. Concentrating collectors are mainly parabolic troughs that use mirrored surfaces to concentrate the solar energy on an absorber tube containing a heat transfer fluid. Evacuated Tube collectors are made of parallel rows of double layer of transparent glass tubes, evacuated for providing insulation, covered with a selective coating that absorbs solar energy well but prevents radiative heat loss.

In this work, the passive indirect SWH system with evacuated tube collector with heat pipe has been used to determine the performance and economic feasibility of using SWH systems in Saudi Arabia in different locations and different climate conditions. The techno-economic viability of SWH system with evacuated tube collector with heat pipe has been determined using the RET Screen program [5]. It has been used in order to estimate the energy produced, fuel savings, GHG emissions and economic indicators.

## LITERATURE REVIEW

The following studies about techno-economic viability and environmental performance of using solar water heaters and research have been conducted in different countries aiming different scopes:

Laborderie *et al* [6] presented a life cycle assessment methodology for the environmental evaluation. They focused on primary energy consumption, potential global warming, effect on ecosystem quality and human health issues. Environmental performances of the different SWH with gas-backup, electrical-backup or no backup are compared with standard hot water systems. Pei *et al* [7] presented a comparison of experimental rig of evacuated tube SWH systems with and without reflector, the set up was done in Hefei in China. The results show that when attaining low temperature water, the evacuated tube solar water heater system without reflector has higher efficiencies than the system with reflector. On the other hand, when attaining high temperature water, the system with reflector has higher efficiencies than the other one. An extensive reviews and analysis to perform and improve the efficiency of solar water heating are presented by Shukla *et al* [8], Sadhishkumar and Balusamy [9], Tiwari and Jaurkar [10] and Veeraboina and Yesuratnam [11]. They gave a detailed review on the design and provide a consolidated on the development of various system components that includes the collector, storage tank and heat exchanger. Ayompe and Duffy [12] analyzed the thermal performance of a SWH system with heat pipe evacuated tube collector with 3m$^2$ using climate data for Dublin in Ireland. The recorded maximum collector outlet temperature was 70.3 $^o$C while the water temperature at the bottom of the hot water tank was 59.5 $^o$C, the annual average solar fraction was 33.8%, collector efficiency was 63.2% and system efficiency was 52.0%. They observed that the use of collector with heat pipe is more efficient than flat plate when operating as a SWH system. Zhang *et al* [13] presented a solar thermoelectric co-generator combining heat pipes with thermoelectric modules in evacuated tubular, which supply both electricity and heat simultaneously. They studied the system from an experimental as well as theoretical view point. They founded that the system is economical and suitable for commercial production and the payback time of this system estimated to be about 8 years. The impact on energy consumption and GHG emissions as well as the techno-economic feasibility of retrofitting SWH systems in the Canadian housing are evaluated by Nikoofard *et al* [14]. They found that the energy savings potential with solar domestic hot water systems in all provinces are similar, while the GHG emission reductions vary significantly due to the substantially different fuel mix used in different provinces.

Rehman and Sulaiman [15] estimated the techno-economic viability of SWH technologies for domestic purpose for different types of collectors using RET Screen software for different climatic conditions in KSA. They found that evacuated tubes solar collectors are better than flat plat collector with respect to solar fraction, higher energy saving, and GHG reduction. Date *et al* [16] gave theoretical and experimental analysis on the transient behaviour of combined SWH with heat pipes and thermoelectric power generation system. They observed that, for a typical house with 5 m$^2$ of available surface area 300 litter of water can be heated to 76 $^o$C during the peak sun hours. Bracamonte *et al* [17] studied the effect of the tilt angle 10$^o$, 27$^o$ and 45$^o$ (to the horizontal) on flow patterns, energy conversion efficiency and the stratification effect experimental as well theoretical for non-pressurized SWH in tropical regions. They found that the tilt angle has significant effect on daily solar energy gain, flow patterns inside the storage tank and stratification. They presented good agreement between the numerical model and experimental measurements. The effectiveness of using SWH with thermosiphon to reduce the energy consumption in South African households was investigated by Kakaza and Folly [18]. The effectiveness of the SWH systems and heat pumps was studied together, by comparing energy consumption, cost and payback period. They found that heat pumps payback period is 4.2 years while the payback period of SWH systems is 7 years. Simulation results showed that, the heat pump consumes 22% of energy in comparison with electric hot water heater, thus saving is 78%. On the other hand, SWH system has a daily energy consumption of 58%, hence saving is 42% of energy in comparison with electrical geyser.

Zaniani *et al* [19] studied the use of SWH system in a school in Chaharmahal va Bakhtiari – Iran using RET Screen program. They presented economic analysis and calculated the capital return of 7.8 years and reduction of fossil fuel of 65%. In addition, they assumed if the government pay 50% of the solar system, the simple payback will be reduced to 2.4 years. The performances of drain water heat recovery (DWHR) units with two solar domestic water heaters (SDWH) in Ontario- Canada have been shown by Tanha *et al* [20]. The first system consists of a flat plate solar thermal collector in conjunction with a gas boiler and a DWHR unit. The second system consists of an evacuated tube solar collector with electric heater and a DWHR unit. The deduced results based on the experimental study showed that the DWHR unit is capable for annual heat recovery of 789 kWh and an overall effectiveness about 50%. The flat plate and evacuated tube collectors based on SDWH systems produce an annual thermal energy output of 2038 kWh (absorber area 2.32 $m^2$) and 1383 kWh (absorber area 2.05 $m^2$), respectively. They concluded that the thermal energy outputs of the two solar systems follow similar trends throughout a typical year. Mujeebua and Subhi [21] presented a review study about solar energy options for buildings in Saudi Arabia. They reviewed the national energy scenarios, national energy policies and initiatives, detailed data of energy consumption in buildings and solar energy utilization in Saudi Arabia buildings.

## WORKING THEORY OF EVACUATED TUBE SYSTEM WITH HEAT PIPE

The solar vacuum tubes consist of a two layers of glass with a vacuum in between the layers. A hollow copper tube is inserted through the length of the tube. This special tube contains a small amount of special liquid that work as heat transfer medium. The hollow chamber is made under vacuum conditions which cause the fluid to vaporize at lower temperatures (30 $^{o}$C) as a result of the low pressure. Copper heat pipes are used because they can absorb and transfer heat very efficiently. This technology allows the energy to be transferred indirectly to the hot water system [22]. Fig. 1 shows the working theory heat pipe in solar collector. The use of heat pipe in solar collector includes the following advantages:

- High heat transfer efficiency.
- Heat is transferred in one direction from the evaporator to the condenser only.
- Heat transfer can occur at small temperature difference between evaporator and condenser.
- Secure system.
- Suitable for all climatic conditions.
- Environmental friendly.

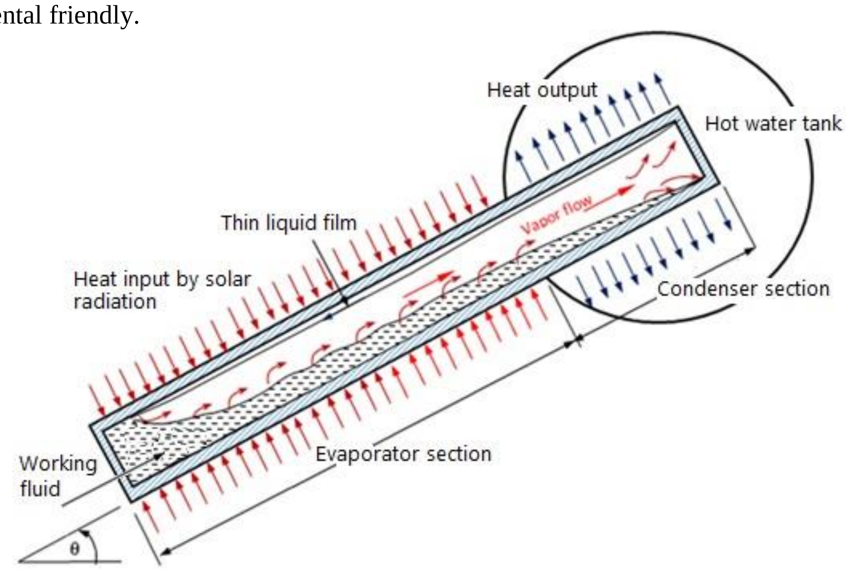


**Fig. 1 Working theory of heat pipe in solar collector**

**Table -1 Technical Data of Evacuated Tube with Heat Pipe Collector**

| | Units | Evacuated tube (TP-HP300) |
|---|---|---|
| Number collectors | - | 30 tubes |
| Collector dimension | mm | ø58x1800 |
| Gross area | $m^2$ | 4.33 |
| Aperture area | $m^2$ | 2.85 |
| Absorber area | $m^2$ | 2.85 |
| Maximum working pressure | MPa | 0.7 |
| Optical efficiency ( $\eta_{.}$ ) | % | 0.63 |
| Absorption | % | 92 |
| 1$^{st}$ order heat loss coefficient ($a_1$) | W/(K.$m^2$) | 1.9 |
| 2$^{nd}$ order heat loss coefficient ($a_2$) | W/($K^2$.$m^2$) | 0.01 |
| Emittance | % | 7.5 |

**Table -2 The Cost and Economic Parameters of Evacuated tube SWH System under Investigation**

| | Units | Value |
|---|---|---|
| Solar collectors + BOS | ($) | 700 |
| Installation cost | ($) | 100 |
| Annual Cost (cleaning) | ($) | 20 |
| Maintenance cost (every 5 years) | ($) | 50 |
| Salvage value | ($) | 100 |
| Electricity cost | ($/kWh) | 0.0533 |
| Inflation rate | (%) | 2.0 |
| Discount rate | (%) | 4.5 |
| Project life | (year) | 20 |
| Incentives and grants | - | 0.0 |
| Debt ratio | (%) | 0.0 |

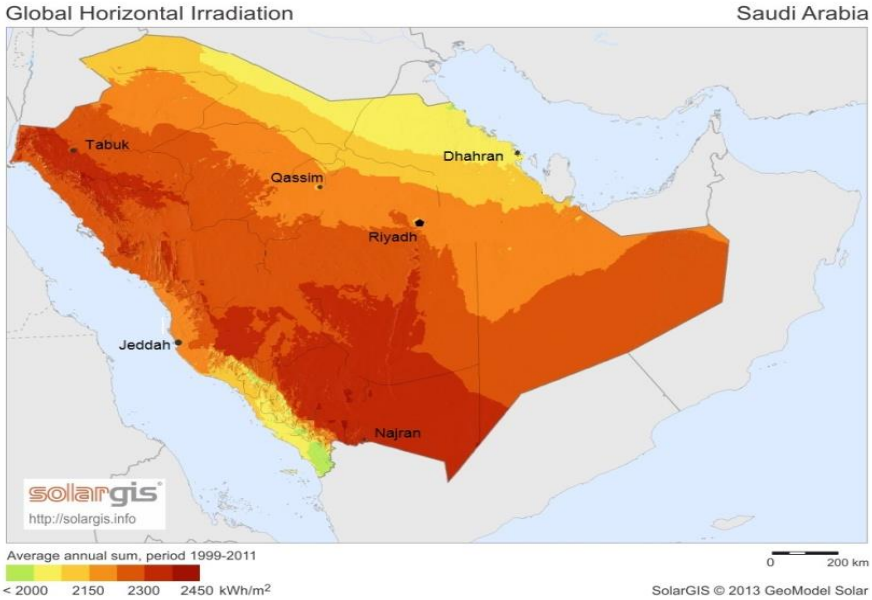


**Fig. 2 Locations of the six sites under study on solar radiation map [25]**

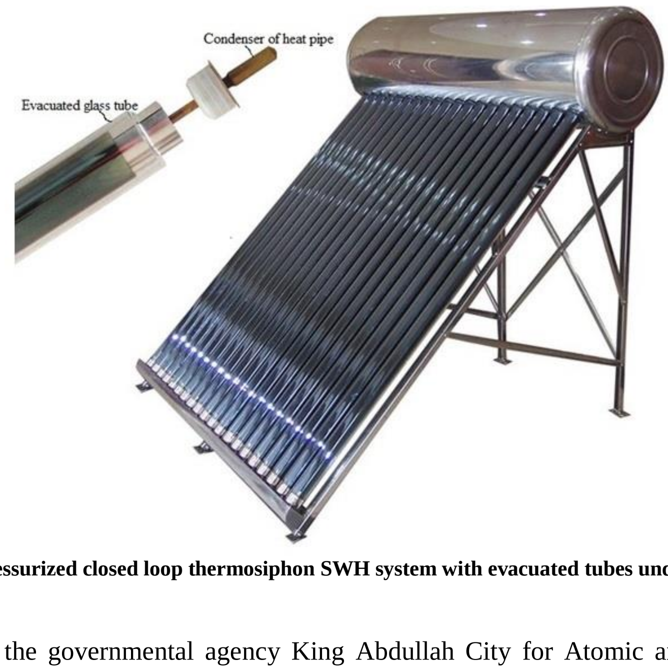


**Fig. 3 The pressurized closed loop thermosiphon SWH system with evacuated tubes under investigation**

## Metrological Data

Saudi Arabia established the governmental agency King Abdullah City for Atomic and Renewable Energy (KA CARE) for renewable energy in 2010 which developed the Renewable Resource Monitoring and Mapping (RRMM) Solar Measurement Network which currently consists of 32 metrological stations deployed in different sites over Saudi Arabia. The RRMM network may be accessed via the interactive, web-accessible Saudi Arabia Renewable Resource Atlas [23], the details of RRMM network are summarized in [24]. Fig. 2 displays the locations of the six sites under investigation in this study which are: Riyadh, Qassim, Jeddah, Dhahran, Tabuk and Najran. These sites are selected to cover all proposed climate zones in Saudi Arabia. The full set of solar radiation and atmospheric data for the last 2 years on average monthly base for the six locations under study are illustrated in appendix.

**Investigation of SWH in Different Locations in Saudi Arabia**

The performance of SWH systems is affected by set of factors such as, solar radiation, ambient temperature, wind speed, tilt and azimuth angles of solar collectors, dust accumulation and solar system components. In the present work, an evacuated tube SWH system with heat pipe collectors has been investigated using RET Screen program to measure its performance in six locations over Saudi Arabia based on the collected data by RRMM network for the last 2 years. RET Screen program uses the efficiency and operating temperature based on the local environmental conditions, including solar irradiance, air and earth temperature, atmospheric pressure, relative humidity and wind speed. A SWH system with evacuated tube collector from TOP ONE SOLAR INC., model (TP-HP300) has been selected for investigation. The SWH system is composed of 30 evacuated tubes with heat pipe collectors, hot water tank upper the collector as shown in Fig. 3. Table 1 shows the technical specifications of the solar collector considered in this study. The frame material of collectors and support structure was an aluminium alloy used to fix the collectors. The system was supposed as being typical in a thermosiphon pressurized indirect (closed) system. Immersion electric boosted element with regulation thermostat is able to safely supply the hot water around the clock with 3.0 kW electric power heater.

**Case Study Assumptions**

The following assumptions have been adopted for the system under investigation in all sites:

- Seasonal efficiency: 94% (from the program)
- Required hot water temperature: 45ºC
- Maximum storage temperature: 60ºC
- Number of family members: 7
- Days of use: 7
- Occupancy rate: 80%
- Minimum supply water temperature: 10ºC
- Maximum supply water temperature: 25ºC
- Solar tracking mode: fixed
- Collector Slope is equal to the site's latitude plus 15º
- Azimuth angle is 0º (i.e. south facing)
- Electrical energy will be used if solar energy is not sufficient.
- Consumption rate during the day is fixed.
- Daily demand of hot water is 54 liter per capita [26].

**Economic Analysis**

The economic analysis of SWH system under investigation has been done based on its economic data shown in Table 2 and the above assumptions using RET Screen program for calculating the following economic indicators

- Simple payback: Simple payback indicates how many years are required to recover the investment for one project compared to another.
- Net Present Value (NPV): is the value of all future cash flows, discounted at the discount rate in today's currency.
- Annual life cycle savings (LCS): is the Levelized nominal yearly savings having exactly the same life and net present value as the project.
- Benefit-Cost (B-C) ratio: is the ratio of the net benefits to costs of the project. Net benefits represent the present value of annual income and savings less annual costs, while the cost is defined as the project equity. B-C ratio greater than 1 is indicative of profitable projects.

The balance of system (BOS) represents all other components which consist of the following: pipes, wires, switches, valves, structures, support frames etc. The economic parameters (Discount rate and Inflation rate) as provided by the Saudi Arabian Monetary Agency (SAMA) in 2015. The cost of installation was estimated in comparison to the traditional construction products and systems to determine the marginal cost of the SWH system.

## RESULTS AND DISCUSSION

**Performance Analysis**

The high levels of solar irradiance for all the six locations under study indicate that there is a great opportunity for utilizing solar water heating technology in Saudi Arabia. Fig. 4 shows the average annual ambient temperature and the annual average of GHI at all sites under study, it is noted that the average GHI in Najran is the highest value which is 6.8 kWh/m$^2$ per day and the lowest is in Dhahran which is 5.81 kWh/m$^2$ per day, while the average annual temperature in Jeddah is the highest which is 30.6 ºC and in Tabuk is the lowest which is 23.3 ºC. The measured values of GHI are in good agreement with old recorded values shown in Fig. 2.

The output of SWH system is subjected to three major factors: the quality of components, conversion efficiency of the collector, the incident irradiation on the surface of collector and the local climatic conditions. Fig. 5 shows the solar fraction and thermal energy output at tilt angle equals to the site's latitude plus 15º and azimuth angle is south facing (0º) under real weather condition for all location. The solar fraction is the amount of energy provided by the solar system divided by the total energy required for an application. It is zero for no solar energy utilization, to 1.0 for all energy provided by solar only. The solar fraction was obtained between 58% in Dhahran and 67% in Najran. Fig. 5 illuminates that, the annual thermal energy delivered by SWH systems in different locations are between a minimum of 4.0 MWh in Dhahran and the maximum of 4.5 MWh in in Najran, which means that each square meter of collector aperture area of SWH system is able to produce 1579, 1509, 1404, 1439, 1474 and 1474 kWh/year for Najran, Tabuk, Dhahran, Jeddah, Qassim and Riyadh respectively. It is also shows that the solar fraction is directly proportional with the output energy. Also, it can be seen from Fig. 5 that the thermal energy output and solar fraction are the same values in the case of Riyadh and Qassim, this is due to they have the same value of GHI (6.13 kWh/m$^2$/day) and little difference in ambient temperature. Fig. 6 shows the annual sum of GHI and a comparison between the energy produced by one square meter of the gross and the aperture area of the system for all locations under investigation. It is also noted from Fig. 6 that the energy production by an aperture unit area (m$^2$) is bigger than the energy produced per gross unit area of the collector by the same ratio of gross area to aperture area approximately. Fig. 7 shows a comparison between the electrical energy consumption in the case of electric-powered water heating system with cases install SWH systems in the locations under study. It is noted that the annual electrical energy consumed in case of electric-powered system is 7.3 MWh per year, while located between 2.4 to 3 MWh per year in case of using SWH system in all six locations under the assumptions mentioned above. Also noted that the consumption of electrical energy is the lowest in Najran and the highest in Dhahran, which is 2.4 and 3 MWh per year respectively. Fig. 7 also shows the cost of electrical energy consumption per year for all cases under study.

Fig. 8 represents the annual savings in energy consumption as a result of using the specified SWH system in all locations under study. The saving amounts is in the range between 8.6 and 9.8 Barrel of crude oil per year, resulted in a reduction in the deployment of carbon dioxide in range between 3.7 and 4.2 tone of $CO_2$ per year. that means, each square meter of aperture area of solar collector is able to reduce $CO_2$ emissions by 1474, 1404, 1298, 1333, 1268 and 1268 kg $CO_2$ per year for Najran, Tabuk, Dhahran, Jeddah, Qassim and Riyadh respectively, taking into account the main source is electrical energy. It can be seen at first, that is a limited savings in energy consumption and redaction of $CO_2$, but when taking into account the number of housing units and the consumption of hot water for non-residential purposes in the Saudi Arabia will be more effective number. Fig. 9 compares between the reduction of CO2 emissions per square meter of gross and aperture area of evacuated tube collector.

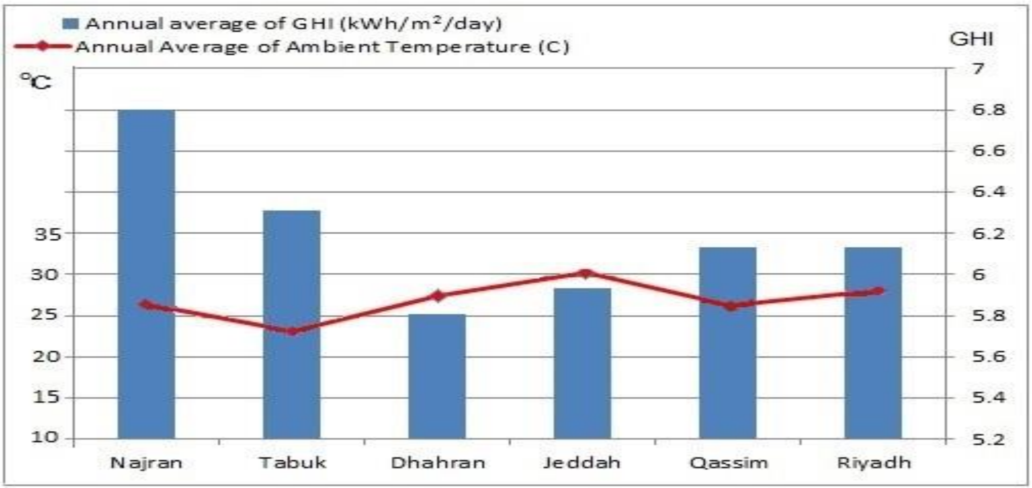


**Fig. 4 Annual average of ambient temperature and GHI of six sites under investigation**

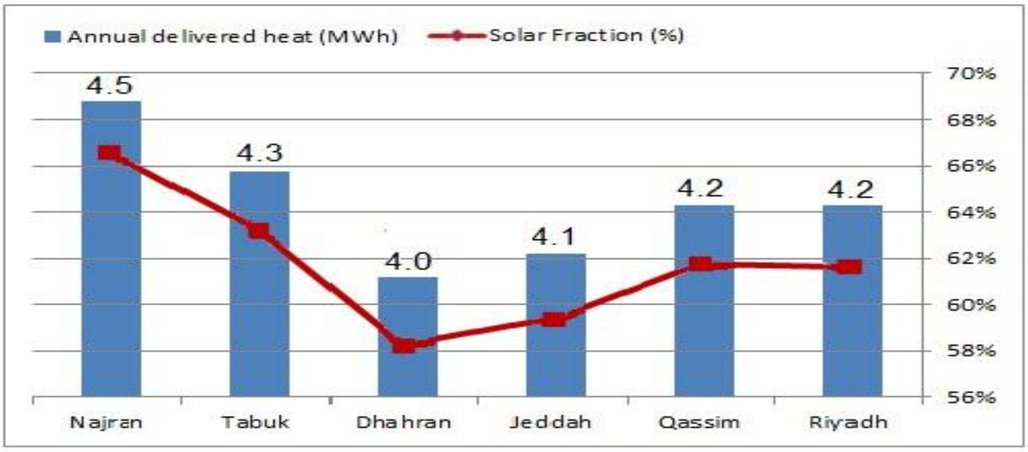


**Fig. 5 Solar fraction and thermal energy outputs for six sites under investigation**

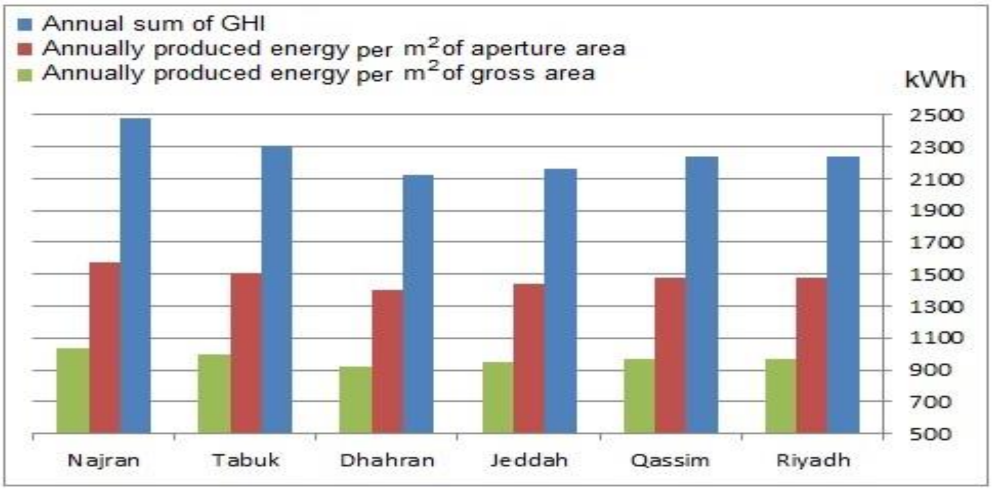


**Fig. 6 Annual sum of GHI (kWh/m$^2$) and energy produced annually per square meter of gross and aperture area of evacuated tube collector**

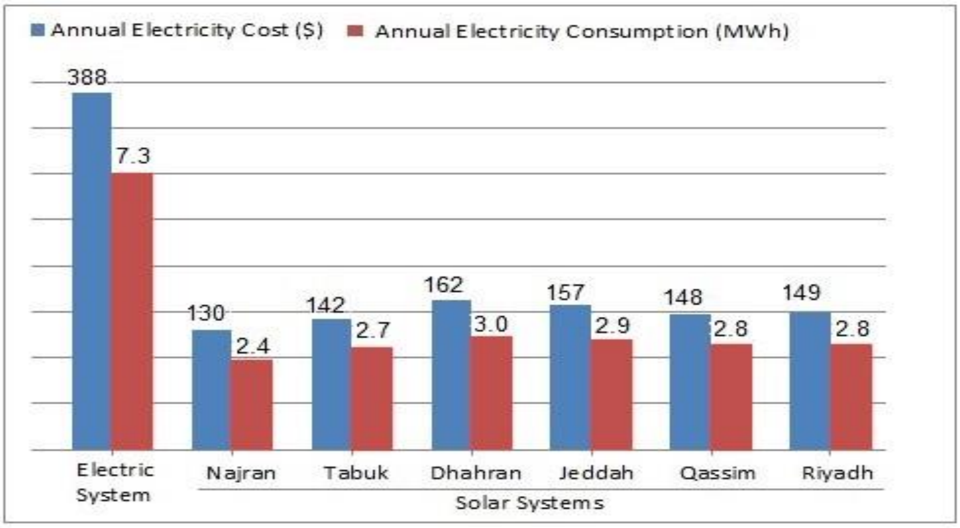


**Fig. 7 Annual energy consumption of using SWH system in the six sites under investigation compared to electric-powered water heating system**

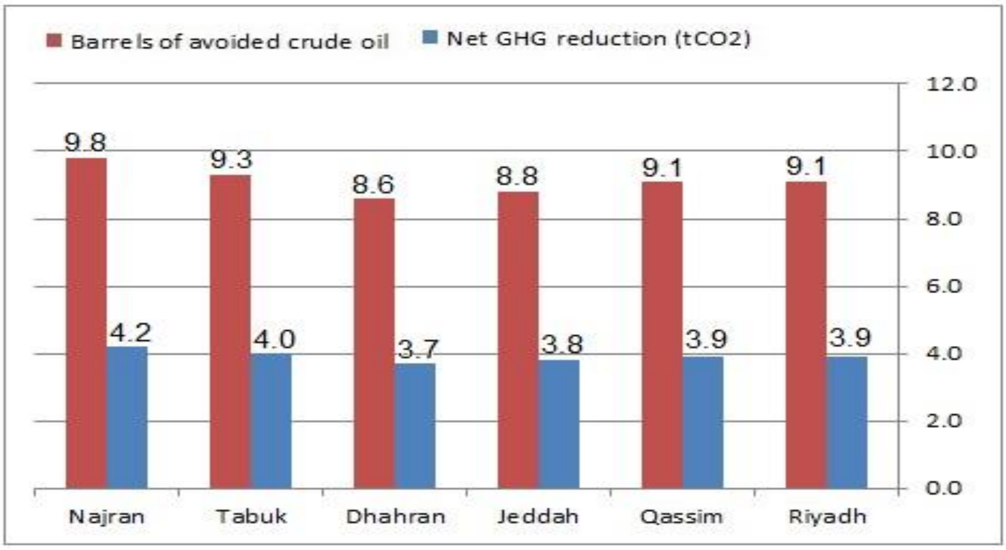


**Fig. 8 Annual savings in energy consumption and reduction in $CO_2$ emissions due to using SWH system in the six sites under investigation**

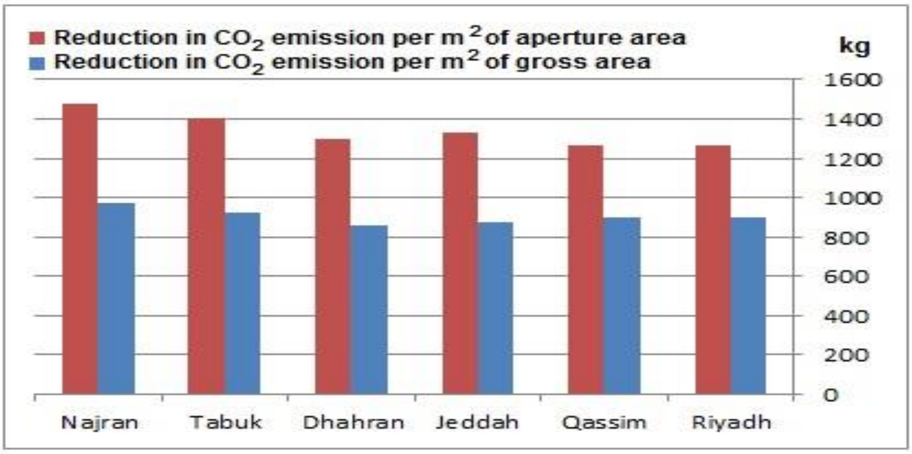


**Fig. 9 Annual reduction of $CO_2$ emissions per square meter of gross and aperture area of evacuated tube collector**

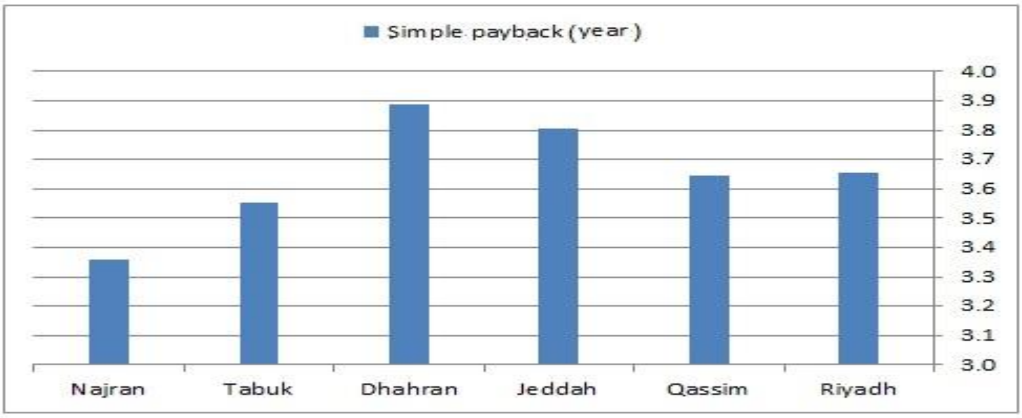


**Fig. 10 Simple Payback time of six sites under investigation**

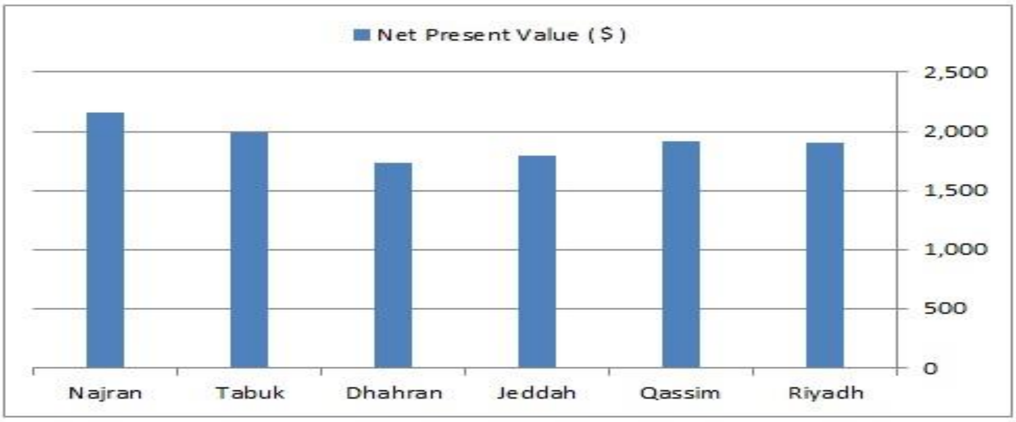


**Fig. 11 Net Present Value (NPV) of six sites under investigation**


**Fig. 12 Annual Life Cycle Savings of six sites under investigation**

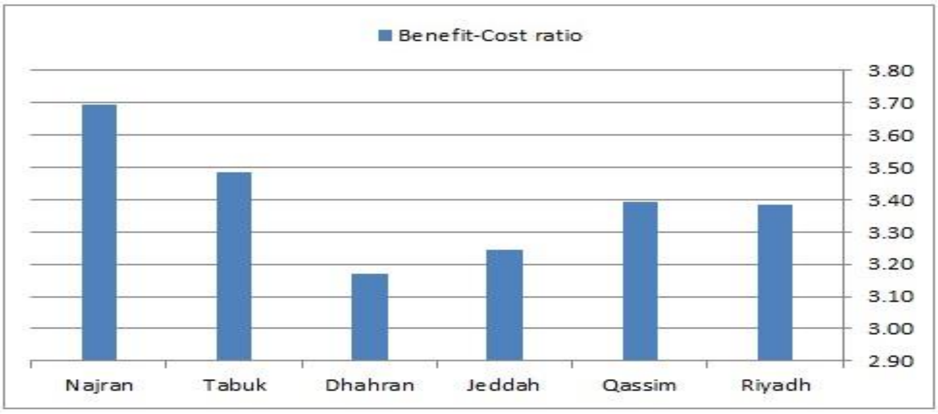


**Fig. 13 Benefit to Cost (B-C) ratio of six sites under investigation**

**Economic Feasibility**

Figures 10-13 show the economic indicators of the Simple payback time, NPV, Annual life cycle savings and B-C ratio respectively. It is clear from this Figs that Najran site is the best among the six sites under investigation with values (3.4 years, 2150 $, 3.7 and 162 $) for payback time, NPV, B-C ratio and annual savings respectively, while Dhahran site is the worst one with values (3.9 years, 1700 $, 3.17 and 132 $) for payback time, NPV, B-C ratio and annual savings respectively, the indicators of other sites are between Najran and Dhahran, Qassim and Riyadh mostly have similar results. By comparing these results with their annual average of GHI and ambient temperature in Fig. 4, it is clear the good correlation between these economic indicators and the corresponding GHI while there is no clear correlation with ambient temperature. By comparing the current results with our previous work (under publication), for investigating the performance of flat plate solar collector in the same locations. It was found the current values of solar fraction reduced by 6%, the annual delivered heat reduced by 8.5%, the annual electricity consumption increased by 18%, GHG emissions reduced by 9%, payback time reduced by 51%, NPV increased by 19%, annual savings increased by 33% and B-C ratio increased by 84%, which mean the flat plate collector is better than the other under investigation conditions.

## CONCLUSION

In the present study, the technical, economic and environmental aspects of utilizing SWH technology have investigated in six sites in Saudi Arabia (Najran, Tabuk, Dhahran, Jeddah, Qassim and Riyadh) for residential sector. This investigation is based on a wider perspective to include the costs, benefits to society and environment. The technical and economic performance of evacuated tube SWH system in all selected locations has estimated using RET Screen program through determining the delivered heat, solar fraction, the reduction in CO2 emissions, the savings in energy and money, payback time, net present value and the benefit to cost ratio. Clearly, the results of economic analysis reveal that utilizing the evacuated tube SWH system with heat pipe is feasible in Saudi Arabia and can compete with conventional energy systems on unit cost basis. Each square meter of aperture area of evacuated tube SWH system with heat pipe is able to produce 1579, 1509, 1404, 1439, 1474 and 1474 kWh/year and in the same time it will reduce the emissions of CO2 by 1474, 1404, 1298, 1333, 1268 and 1268 kg/year for Najran, Tabuk, Dhahran, Jeddah, Qassim and Riyadh respectively. As a result, the expected reduction in electricity consumption in case of deploying the SWH technology in Saudi Arabia may reach up to 8%. The payback time for evacuated tube SWH system with heat pipe for all selected sites is between 3.4 - 3.9 years which is reasonable. Normally, the results of this study with current prices of energy emphases the economic feasibility of using SWH systems in Saudi Arabia.

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