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Article

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Research paper

Performance evaluation of solar water heating system with heat pipe evacuated tubes provided with natural gas backup



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ABSTRACT

Present work is focused on building a TRNSYS simulation model of solar water heating (SWH) system using heat pipe evacuated tubes, hybridized with conventional fuel (i.e., natural gas) backup to provide uninterrupted thermal energy supply. An experimental facility was developed to validate the simulated model. Further, the performance of hybrid evacuated tube solar water heating (ETSWH) system was evaluated when it was thermally powered by a solar collector and conventional backup fuel. It was found that 23%–56% backup fuel could be saved by replacing conventional (gas) water heating system with the hybrid ETSWH system, which would additionally result in reduced greenhouse gas (GHG) emissions. The effects caused by concerned performance parameters, like water tubing insulation, differential temperature controller presence, and collector's plane area variations were also investigated. A comparison was conducted to reveal the performance of hybrid ETSWH system against a hybrid flat plate SWH (FPSWH) system. The findings show that hybrid ETSWH system is more efficient and eco-friendly with 1.87 benefit–cost ratio value and would result in annual natural gas savings of 8.79×10^5 kWh that would lead to 175.539 U.S.-tCO₂ emissions reduction, whereas hybrid FPSWH system with 1.64 benefit–cost ratio value would result in 6.45×10^5 kWh annual natural gas fuel savings.

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1. Introduction

Energy is the central cohesive force for sustainable development and economic growth. In recent years, extensive consumption of conventional fossil fuels (that accounted for 81% of total primary energy supply (International Energy Agency, 2019) to fulfill energy thirst, resulted in two main issues (Said and Mehmood, 2017): rapid depletion of fossil fuels reserves and the environmental concerns emerged due to combustion of high carbon content containing crude oil products. These emerging fears divert the world's focus towards sustainable strategies, that intend to make the systems environment-friendly, economically viable and energy efficient (Suhariyanto et al., 2017). Clean energy systems based on renewable energy technologies could play an appreciable role in improving the energy security, and to mitigate the environmental concerns by replacing the conventional fuels

in four discrete zones like electric power generation, transportation of fuels, hot water usage and off-grid power services. In this concern, sustainable development goals (SDGs) have been introduced by United Nations with 2030 agendas focus to increase the renewable energy share in total primary energy supply globally (Abhi Chatterjee et al., 2019). Renewable energy share in global energy mix has been continuously increasing and has already surpassed the targets in 2010 that were projected for 2020 (Renewable Energy Policy Network for the 21st Century, 2019). Renewable energy share of global final energy consumption remained at 20.5% at the end of 2016, and this figure experienced the most significant increase in 2017 (Renewable Energy Policy Network for the 21st Century, 2019).

Among renewable energy technologies, solar seems a promising source and its harnessing rate has been increasing ~30% per annum since 1980 (Raisul Islam et al., 2013). Solar technology has two primary usage domains: solar thermal heating/cooling, and solar photovoltaic. The economic benefits possible to be attained as a result of SWH technology application can be realized through conventional fuel savings achieved and a appreciable reduction in environmental emissions (Porrás-Prieto et al., 2018).

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Nomenclature

FrU_L	Coefficient of thermal losses
$Fr(\tau\alpha)$	Coefficient of optical efficiency
η_c	Collector efficiency
Q_u	Useful energy gain of collector (J)
$\tau\alpha$	Transmittance-absorptance product
U_L	Collector overall heat loss coefficient (W/m ² °C)

Abbreviations

BCR	Benefit–cost ratio
CF	Cash flow
CF ₀	Zeroth Cash Flow i.e. Investment
CF _i	ith Cash Flow
ETC	Evacuated tube collector
ETSWH	Evacuated tube solar water heater/heating
FPC	Flat plate collector
FPSWH	Flat plate solar water heater/heating
GHG	Greenhouse gases
IRR	Internal rate of return
NPV	Net present value
PVC	Polyvinyl Chloride
SWH	Solar water heater/heating
TRNSYS	Transient system simulation

SWH technology is playing a significant role in domestic and industrial sectors of many countries by saving their conventional fuels being consumed for water heating purpose, where 80% of total solar thermal installed capacity accounts for domestic applications (Franz Mauthner and Spörk-Dür, 2015). Energy consumption in buildings (in the form of water/space heating and cooling) accounts for one-third of total final energy consumption, of which renewables supply only 9% (De Falco et al., 2017). The total global solar thermal heating and cooling installed capacity has become 456 gigawatts-thermal with 5% increase in 2016 and is continued to increase exponentially. As of today, China is the leader of the global solar thermal market, while Turkey, Brazil, India, and the United States are the followings in the top five countries list (Renewable Energy Policy Network for the 21st Century, 2019).

The performance of renewable energy-based systems is specific location concerned, especially in the case of solar and wind technologies. As the performance of these renewable technologies largely depends upon weather conditions. In this perspective, several researchers studied the SWH collectors (Hohne et al., 2019), primary building component of the SWH system, using both experimental and theoretical approaches. Hussein (2007) developed a modified simulation model for wickless flat plate solar collector with cross-flow heat exchanger and validated his model (Azad, 2008) by investigating the thermal behavior of gravity-assisted heat pipe, solar collector, using a number of transfer units (NTU) method based theoretical and experimental approaches. Budihardjo and Morrison (2009) developed a TRNSYS model for evaluating the comparative performance of the water-in-glass evacuated tube and the flat plate SWHs. They concluded that a 30-tubes ETC system resulted in slightly lower energy savings compared to that yielded by a two panel (of 3.7 m² area) FPSWH system.

Ayompe et al. (2011), developed a TRNSYS model and performed experiments in temperate climates for forced circulation

SWH systems using FPC and heat pipe ETC. The model was validated by comparing the modeled and measured data collected at Dublin, Ireland. They concluded that there were 16.9% and 18.4% mean absolute errors between the modeled system outcomes and the experimental figures for FPC and ETC systems respectively. Basil et al. (2014), used the TRNSYS simulation model for investigating the performance of ETC at different concentration levels by predicting the power generation. They concluded that the thermal performance of ETC with high concentration ratios would provide appreciable improvement at receiver's output point. Banister et al. (2014) worked on the development of the TRNSYS simulation model of the solar-assisted heat pump. Their model was validated by using an experimental setup, which consisted of a solar collector, heat pump, storage tank, and heat exchanger. Shihabudheen and Arun (2014) investigated the performance of hybrid photovoltaic-thermal water heating system installed at Calicut using both experimental and TRNSYS model-based analytical approaches. They concluded that there was a 4% expected increase in the efficiency of the PV module when it was working with different flow rates of water, used to cool down the collector. Liu et al. (2017) studied the heating effect in spatial partition and whole space heating conditions through TRNSYS simulations.

The solar thermal collector is the main building component of a SWH system. It captures the incident solar radiations and converts them into useful energy. Different researchers developed TRNSYS and mathematical models to optimize the performance of solar thermal collectors installed at different locations of the world with different tilt angles. For example, Shariah et al. (2002), carried out TRNSYS simulations for the northern and southern parts of Jordan. Duffie and Beckman (2013), elaborated the design and performance of a solar thermal collector, considering mathematical relations along with its characteristic features like FrU_L , $Fr(\tau\alpha)$, Q_u , U_L , η_c , $\tau\alpha$, etc., and their operating values. All the studies done so far were for solar thermal collector only with focus on domestic application. Any kind of model proposing the hybridization of solar thermal collector with conventional fuel (i.e. natural gas) for domestic applications is not available in literature. Furthermore, as of today, no such study has been carried out for evaluating the performance of solar thermal technologies in Pakistan territory, in spite of having indefinite solar potential even higher than the global solar market leaders like China, Germany, Malaysia.

The aim of this work is to develop a Hybrid TRNSYS simulation model of solar thermal water heating system using heat pipe ETC, hybridized with conventional fuel (i.e., natural gas) with focus of domestic sector application. Basic experimental facility was developed to validate the hybrid simulation model. A validated simulation model was used to examine the performance of hybrid ETSWH system and work was focused to answer the following questions:

- How much conventional fuel (i.e. natural gas) can be saved against the harnessed useful energy of ETSWH system?
- What will be the effect of water pipeline insulation, and differential temperature controller presence in terms of natural gas fuel savings?
- What will be the effect of variations in the thermal collector's plane area on ETSWH system performance?
- How much efficient the ETSWH system is more than the FPSWH system considering natural gas fuel savings as a decision parameter?
- How much ETSWH and FPSWH systems are eco-friendly?
- What is the comparative financial viability of ETSWH and FPSWH systems in terms of NPV, IRR, payback period, and BCR values?

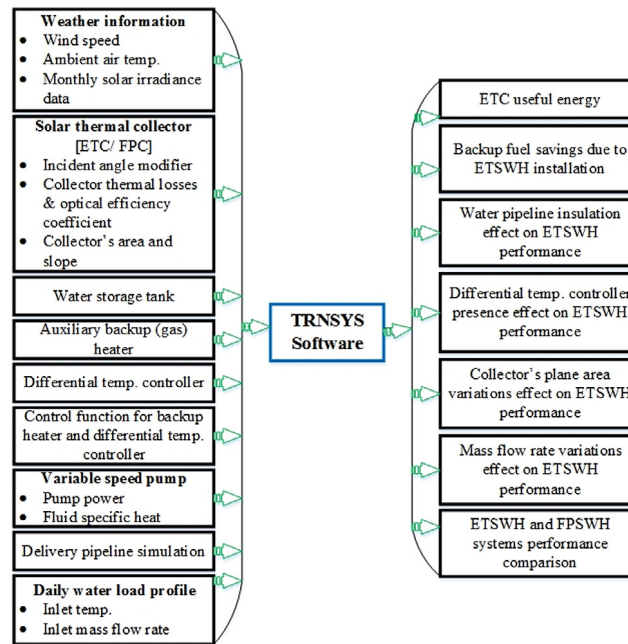


Fig. 1. Methodology steps: input components and focused outcomes.

The paper is organized as: modeling methodology, simulation parameters description and weather information of the selected location (i.e. Islamabad, Pakistan) are explained in Section 2. Experimental setup and procedure is described in Section 3. Validation of simulation model, performance examination of TRNSYS hybrid ETSWH system and its comparison against simulated FPSWH system are elaborated in Section 4 (i.e. results and discussion). The eco-friendliness of simulated hybrid systems in terms of GHG emissions reduction and the comparative financial viability of hybrid ETSWH system against hybrid FPSWH system considering economic parameters is described in Section 5. Section 6 represents the conclusion along with recommendations are given.

2. Modeling methodology

A domestic scale SWH system was modeled in Transient Simulation software (TRNSYS) (Ayompe et al., 2011) a quasi-steady state simulation program, using a non-concentrated solar thermal collector, considering a TRNSYS validated model developed by Ayompe et al. (2011), as a reference, and developed a new hybrid one. The modeled SWH is hybridized with conventional fuel through a backup gas heater to provide auxiliary heat energy required to attain desired hot water temperature, and for continuous hot water supply throughout the day even during non-sunny hours. The adopted software methodology is composed of specific input providing components and focused outcomes, as depicted in Fig. 1.

2.1. TRNSYS simulation model and parameters description

The main building component of TRNSYS model is solar radiant heat energy collector which is ETC (type 71), (and FPC (type 73) is the only case when comparison with ETC was performed). To hybridize the SWH system with conventional fuel for providing the backup, auxiliary natural gas fuel based tank heating device (type 1226-Gas) is connected. Other additional components interconnected to build up a hybrid model, are: weather information including in-plane solar radiations (global, direct and diffused radiations), wind speed, humidity and air temperature

(type 99), hot water drawn profile (type 14b), water storage tank (type 4a), forcing function (type 14), differential temperature controller (type 2b), variable speed pump (type 3b), pipe duct (type 31), water tempering valve (type 11b), water mixing valve (type 11h), and online simulation outcome plotter (type 65c). Complete flow of information about the modeled hybrid SWH system is shown in Fig. 2, and TRNSYS simulation model is shown in Fig. A.1 (Appendix).

SWH system mainly consists of a non-concentrated solar thermal collector, hot water storage tank, water load profile, water tempering valve, variable speed pump, and weather data files. The main add-on of the new model is the presence of integrated backup heating source to fulfill heat energy demand during the non-sunny time for domestic users. In this study, the effect of differential temperature controller presence and pipe duct insulation is also investigated. The working of the backup heating source is monitored by a control signal that turns the backup heater on/off as water temperature inside the storage tank goes below/above the set point. The input parameters of the modeled hybrid SWH system are listed in Tables 1 and 2. The hybrid SWH system was modeled for a house occupied by five family members. Hot water storage tank of volume 75 gallons (~284 L) was estimated through the rule of thumb method (Plante, 2014) used for sizing a solar domestic hot water system and market observations of the people daily hot water usage rate, keeping in view the market availability factor too. Both heating elements of the storage tank were switched off as auxiliary tank heating device consuming natural gas was equipped with the system for providing backup. The hot water demand profile for domestic usage (especially during winter season months) is estimated through interaction with system designers and domestic users and shown in Fig. 3. Mass flow rate value was set from the required volume of the hot water drawn value. Solar thermal collector's area value set equals to 1.7 m² which was nominalized through optimization process for the coldest day of the year (1st Jan: according to the meteorological provided weather data), considering auxiliary backup fuel (i.e. natural gas) required to meet the demand as indication parameter. To maximize the solar incident radiations value, incident angle modifier setup file provided by TRNSYS database was also inserted in collector's settings. Hot water temperature

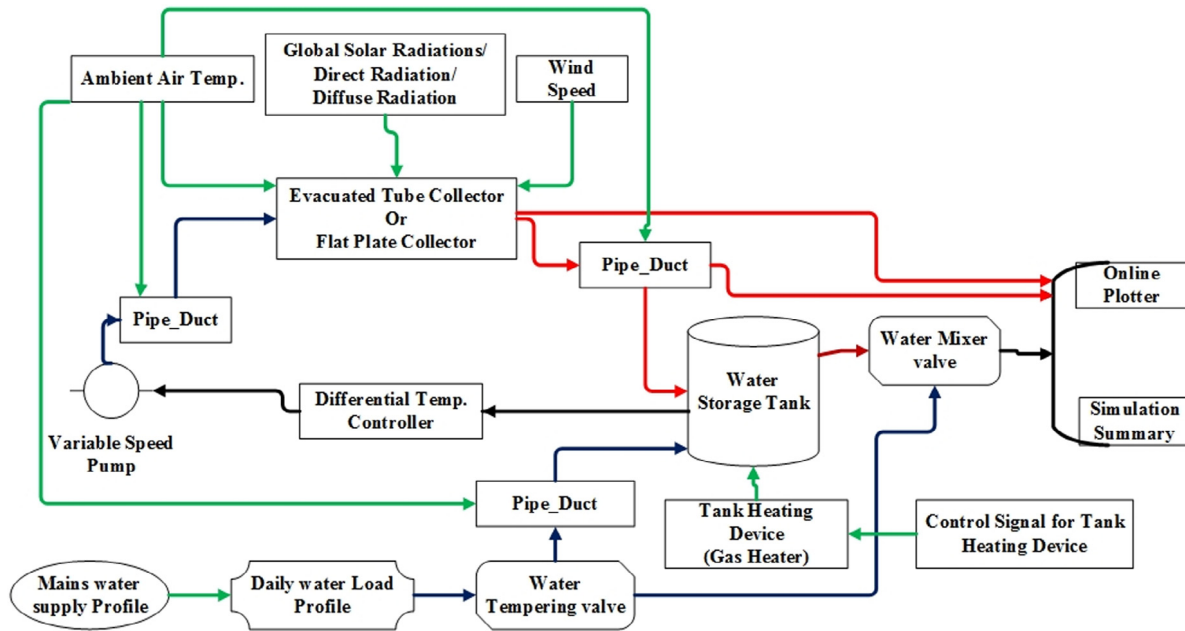


Fig. 2. TRNSYS model: information flow diagram of the modeled hybrid SWH system [green color is for input information of system components; blue color is for normal water supply; red color is for hot water]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

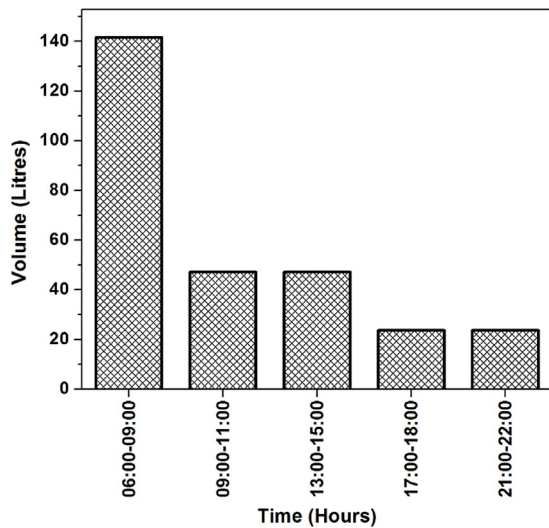


Fig. 3. The domestic hot water demand profile of the residents of selected location for study (i.e. Islamabad, Pakistan) for modeled hybrid SWH system.

monitored by a differential temperature controller was set equals to 55 °C, based on the rule of thumb method (Plante, 2014) and market surveys, with upper and lower dead band (ΔT) of 5 °C. Differential temperature controller also protects the system from overheating and water freezing within the pipe tubes phenomena. Water tubing was thermally insulated with 2 mm thick PVC coating to reduce the heat losses (Deeble, 1994), that could occur due to the temperature difference between inside flowing hot water and outside colder environment.

The main assumptions used for modeling the hybrid SWH system include:

- Natural gas is taken as a backup fuel as it is the primary fuel being consumed in Pakistan for water heating purpose because it is cheaper than liquid oil products.

Table 1

Solar thermal collector specifications.

Factor	Value	
	FPC	ETC
Number of collectors in series	01	01
Collector area (m ²)	1.7	1.7
Fluid specific heat (kJ/kg k)	4.190	4.190
Absorber plate emittance	0.7	-
Absorptance of absorber plate	0.8	-
Number of covers	01	-
Index of refraction of cover	1.526	-

Table 2

Modeled hybrid SWH system input parameters.

Factor	Value
Household parameters	
Daily hot water use (L/d)	284
Operating days per week (d/w)	7
Hot water storage tank parameters	
Storage tank capacity (gal)	75 (~284 L)
Tank loss coefficient (W/m ² K)	0.317
Hot side temperature (°C)	55
Cold side temperature (°C)	5 ~ 25
Differential temperature controller parameters	
High limit cut-out (°C)	60
No of oscillations	05
Monitoring hot water Temp. (°C)	55 ± 5
Auxiliary tank heating device (Gas heater)	
Heating capacity (kJ/kg)	23,811
Thermal efficiency (fraction)	0.758

- Collector slope is adjusted to the latitude value of the location as the modeled system has to fulfill hot water demand throughout the year (Walker, 2016).

2.2. Meteorological information

Weather conditions are critical parameters for evaluating the system's performance based on renewable energy sources,

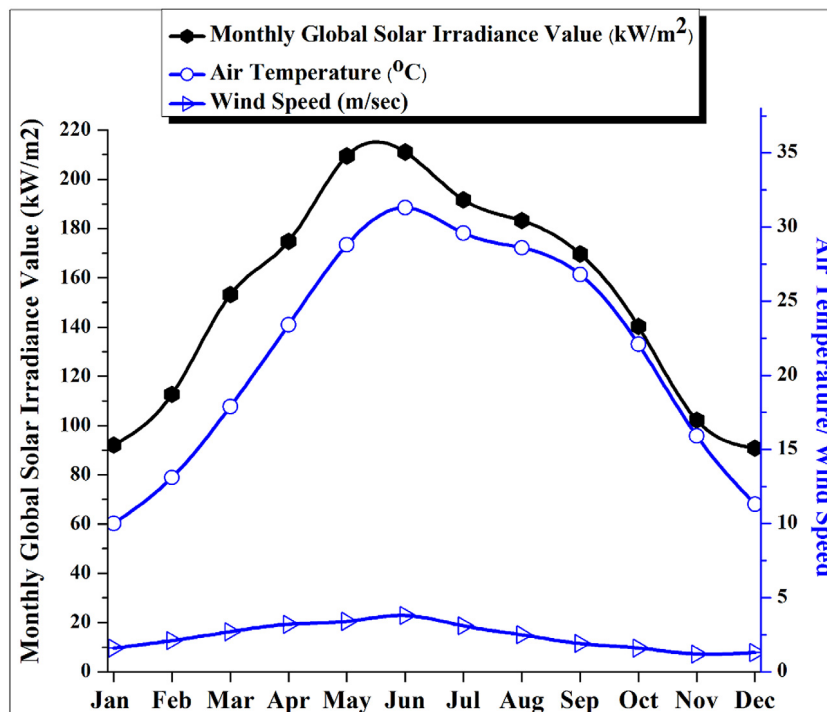


Fig. 4. Weather information of selected latitude position (i.e. Islamabad, Pakistan): solar radiation, air temperature, and wind speed.

specifically for solar and wind. Weather information, including global solar radiation, air temperature, and wind speed, of Islamabad city (having latitude = 33.6°N and longitude = 73.1°E) provided by meteonorm are depicted in Fig. 4.

3. Experimental setup and procedure

Experimental setup (shown in Fig. 5) was developed to validate the TRNSYS simulation model. The developed system was installed on the flat ground surface in National University of Sciences and Technology, Islamabad, Pakistan. The installed system mainly consists of evacuated tube solar thermal collector, storage tank, and pressure hose pipe insulated with cotton wool and foam. Collector tubes were in a south facing direction inclined at 33.6°N, equals to latitude position of the location. A multi-fuel furnace (shown in Fig. 6) was manufactured using mild steel sheets of corrugated galvanized iron (CGI) material of varying thickness. Outer wall of the furnace was of 20-BWG (Birmingham Wire Gauge) and inner wall was of 18-BWG. Glass wool insulation was provided between outer and inner walls of the furnace. Manufactured furnace was hybridized with evacuated tube collectors to provide back-up and to make the developed SWH system hybrid, having two combustion chambers: one for natural gas fuel combustion and other for coal or wood combustion in-case of natural gas fuel shortage, operates on 0.758 fractions thermal efficiency. Multi-fuel furnace has automated air ventilation sliding mechanism (depicted in Fig. 6(b)) that controls the furnace operation in response to sensor's signals against setpoint of hot water temperature equals to 55 ± 5 °C. It means that the ventilation duct gets opened as water temperature at the outlet falls below 50 °C. This opening of the ventilation duct sends a signal to start the combustion process. Therefore, the combustion process could start when the useful energy amount harnessed by ETC is not enough to provide the hot water at the desired set temperature.



Fig. 5. Experimental set-up: heat pipe evacuated tube manipulate connected to the hot water storage tank and multi-fuel furnace.

After the development of experimental setup, experimental measurements were noted for two days during August using 20 L/h water flow rate from dawn to dusk hours. The focus was kept on measuring the collector's outlet hot water temperature and solar irradiance power available during sunny hours. Collector's outlet hot water temperature was measured using a digital thermocouple (T-type) with $-50 \sim +300$ °C temperature measurement range, 0.1 resolution, and ± 1 °C accuracy for $-20 \sim +80$ °C measurement range and ± 3 °C accuracy value for $+81 \sim +249$ °C temperature measurement range. Solar irradiance power was measured using a digital light meter having 0–50,000 lux measurement range with $\pm 5\%$ accuracy.

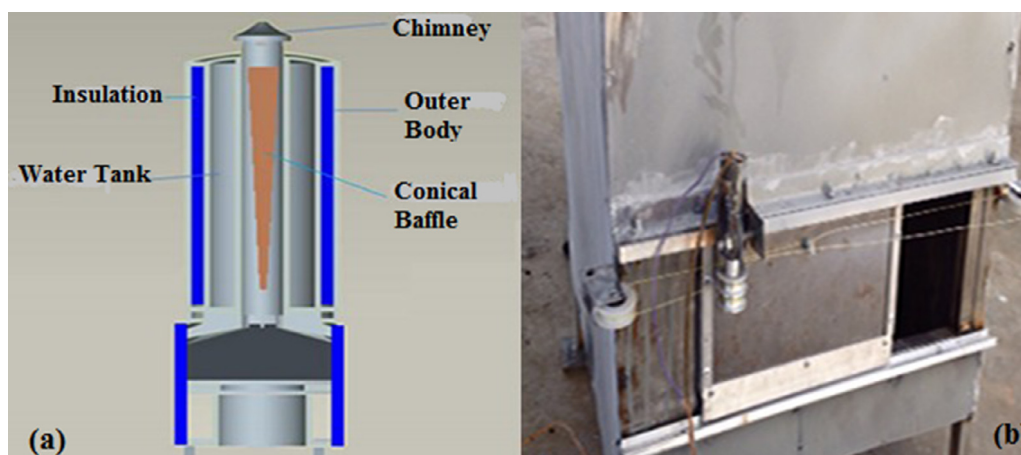


Fig. 6. Multi-fuel furnace: (a) CAD model of the furnace with water storage tank; (b) Air ventilation sliding mechanism of the furnace.

4. Results and discussions

Results based on solar thermal collector's harnessed useful energy, collector's outlet hot water temperature and backup fuel (i.e. natural gas) savings are presented and discussed. These experimental and simulation outcomes are addressed as:

- i. Experimental validation of TRNSYS simulation model
- ii. Simulated hybrid ETSWH system's performance evaluation

4.1. Experimental validation of TRNSYS simulation model

The experimental performance of the developed hybrid system was focused on measured collector's outlet hot water temperature and solar irradiance power available during sunny hours (i.e. 7:00–19:00 h). Results were concluded with the cumulative thermal efficiency value of the thermal collector. Experimental measurements were taken for two days of August month, and are compared with simulation outcomes as depicted in Fig. 7. Analysis of Fig. 7 shows that both parameters, i.e., available solar irradiance and collector's outlet hot water temperature, have maximum values for 12:00 h in both experimental and simulation scenarios. Overall analysis of the results show that there is 5–9% precision error between experimental and simulation outcomes of the collector outlet hot water temperature. The averaged thermal efficiency of the evacuated tube solar thermal collector calculated using experimental data was 0.49 fractions, however using simulation outcomes this thermal efficiency value remained 0.52 fractions.

4.2. Simulated hybrid ETSWH system's performance evaluation

The performance of hybrid ETSWH system was evaluated focusing collector's useful energy harnessed and the savings in conventional backup fuel (i.e. natural gas) achieved as a result of replacing gas water heater with a hybrid ETSWH system. Water tubing insulation, the presence of differential temperature controller, and collector's plane area variations effects were also observed considering natural gas fuel savings.

4.2.1. ETC useful energy

Useful energy delivered by the solar thermal collector is the function of the solar fraction (i.e., solar irradiance power incident on water tubes surface) of the system. In the current scenario, a solar fraction of hybrid ETSWH system remains in 47%–85% range annually. During summer months (May–Sep), solar fraction of the system remains in 80%–85% range. However, during Feb–Apr and

Oct–Nov, the solar fraction of the hybrid ETSWH system lies in 59%–75% range. Only during Dec and Jan months, a solar fraction of the hybrid system remains in 47%–50% range with a minimum value for the Jan month.

Useful energy harnessed by ETC is plotted against monthly available solar radiation, as shown in Fig. 8. It is observed that the increase in global solar irradiance value results in increased ETC useful energy harnessed. From the results shown in Fig. 8, the trend is not followed for Jan and June. In these months, the global solar irradiance values increased compared to that of the respective previous months, but ETC useful energy harnessed values get decreased. The global solar radiations have two main components: the direct radiation component and the diffused radiation component. Among these, the direct component has more effective solar thermal energy intensity value compared to that of the diffused component. This means that a higher value of direct radiations component results in a larger value of useful energy harnessed by the solar collector. That is why; as we move from Dec to Jan, the monthly global solar irradiance value increased by 1.42% but there was a 10.02% decrease in ETC useful energy harnessed. This is because of a decrease in a direct component of global solar radiations by 33.4% in contrary to an increase in global solar irradiance. Similarly, as we move from May to June, the global solar irradiance value increased but the harnessed useful energy value decreased. It is because the increase in diffuse radiation component is greater than that of the direct component, while the direct radiation component value remains the same in both months.

Another interesting observation is that as we move from July to Aug, the decrease in global solar irradiance value accompanies the increase in direct radiation component by 2.12%, but the useful energy value harnessed by ETC decreases. The reason is the number of sunshine hours available during that month. The study reveals that the number of sunshine hours available in August were 5.99% less than that of July. Hence, instead of the increase in direct radiation component value, the useful energy value harnessed by ETC decreased in August compared to that of July. Nevertheless, for the remaining months, the increase in global solar irradiance value accompanies the increase in direct radiations component. Consequently, higher harnessed useful energy value was found for each month compared to the last month value and vice versa. Overall ETC system can harness monthly useful energy value in $1.81 - 4.87 \times 10^5$ kWh range against monthly global solar irradiance value available in 90.8 – 211.1 kWh/m^2 range, which would result in natural gas fuel savings.

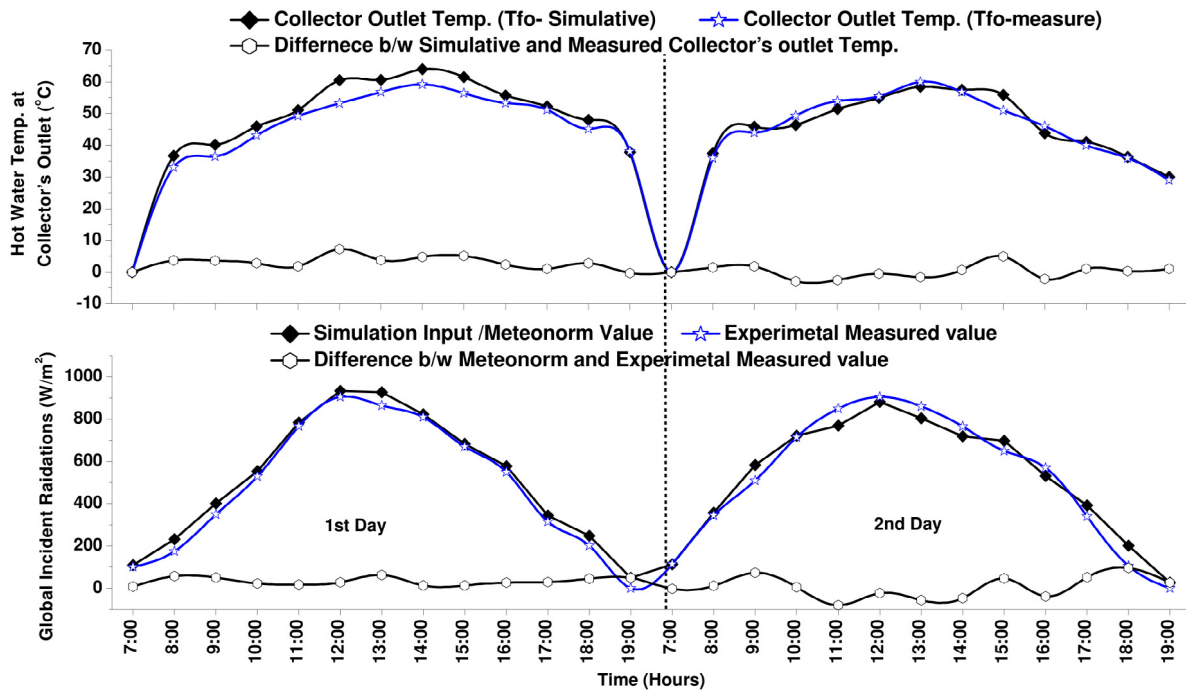


Fig. 7. TRNSYS simulation model validation through experimental and simulation results comparison.

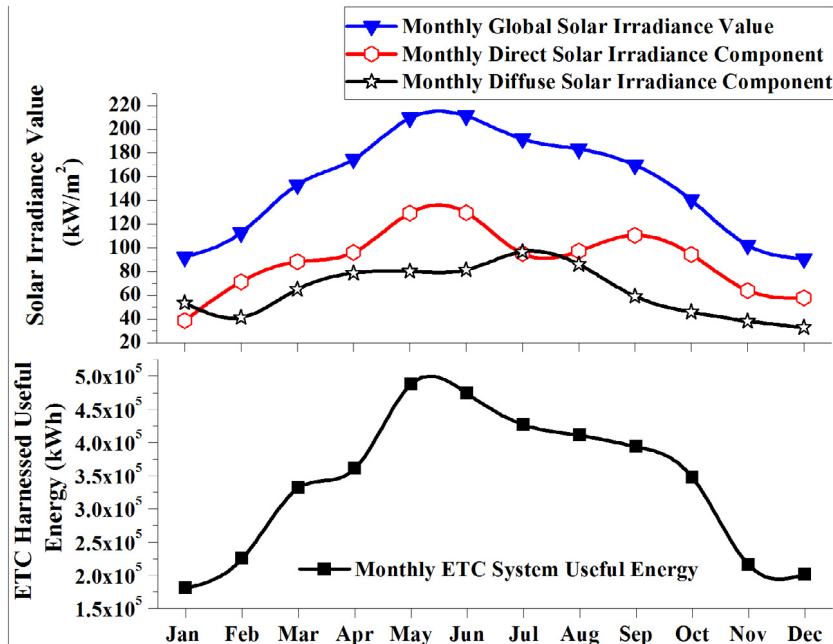


Fig. 8. Monthly averaged useful energy harnessed by ETC.

4.2.2. Hybrid ETSWH system's performance regarding backup (natural gas) fuel savings

Natural gas is one of the major conventional fuels being consumed for water heating purpose. Although Pakistan has one of the world's largest natural gas reserves, still faces a severe natural gas shortage. Fig. 9 depicts how much backup (gas) fuel could be saved by replacing conventional gas water heater with a hybrid ETSWH system. The analysis shows that possible monthly natural

gas fuel savings values lie in $4.7 - 9.6 \times 10^4$ kWh ($\sim 159.4 - 327.2$ mmBtu) range. Total annual natural gas fuel savings possible to be achieved is 8.79×10^5 kWh ($\sim 2.998 \times 10^3$ mmBtu) through the application of a hybrid ETSWH system rather than using a gas water heater. The possible percentage of monthly backup (natural gas) fuel savings are shown in Table 3.

Results confirm that the backup fuel savings in June month has the highest value while in Jan month has the lowest value.

Table 3

Monthly percentage backup conventional (gas) fuel savings possible as a result of replacing the conventional gas water heater with a hybrid ETSWH system.

Month	Percentage backup fuel savings	Month	Percentage backup fuel savings	Month	Percentage backup fuel savings
January	23.69%	May	42.79%	September	54.87%
February	23.89%	June	55.71%	October	45.80%
March	31.08%	July	42.86%	November	33.22%
April	38.78%	August	55.33%	December	25.98%

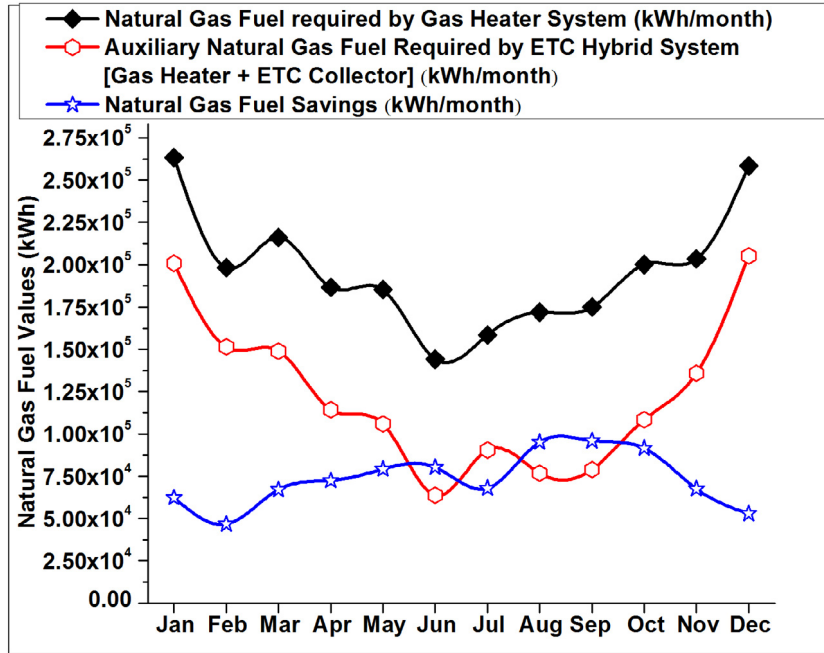


Fig. 9. Backup (natural gas) fuel savings as a result of replacing the conventional gas water heating system with hybrid ETSWH system.

The higher the value of useful energy harnessed by ETC, the greater would be the backup fuel savings as observed from Sep to April (winter season) months. The analysis contradicts from the trend for May–Aug months. As we move from May to June, the useful energy harnessed in June was less than that of May, but the backup fuel savings remained higher. This is because the backup fuel savings are also linked with air temperature: the higher air temperature leads to smaller ΔT value (the difference between the temperature of the inside flowing hot water and the outside ambient temperature). Hence, less backup fuel was required to fulfill the demand for the desired hot water. Therefore, 30.92% less number of hours are required during June compared to May for which the auxiliary backup (gas) heater should remain switched on to fulfill the demand of desired hot water, consequently higher backup fuel savings are possible to be achieved in June.

In July, less backup fuel savings could be achieved than that of Aug, while, the useful energy delivered by ETC during July has greater value compared to that of Aug month. The reason is; Aug month has a greater number of available sunshine hours. The number of hours for which backup (gas) heaters are required to turn on is 20.05% higher for July than that in Aug. Hence, the natural gas fuel savings that could be achieved during July are less compared to those of Aug.

4.2.3. Effect of water tubes insulation on hybrid ETSWH system's performance

Water is delivered from source to storage tank, collector and finally to end user via pipe ducts. As water flows through the tubing, heat transfer takes place between inside flowing hot water

and outside ambient, through conduction because of temperature difference. To reduce the conduction heat losses through the tube wall, a 2 mm polyvinyl chloride (PVC) insulation coating was used. It resulted in 42.56% reduction in heat loss coefficient when the ambient average wind speed was equal to 2.4 m/s (Deeble, 1994). As shown in Fig. 10, the backup (natural gas) fuel savings as a result of water tubing insulation effect are tabulated in Table 4.

Outcomes analysis shows that the backup fuel savings have the highest value in Jan month, when it has low ambient temperature and wind speed. The least savings values are found in June when it has the highest temperature and wind speed. It is because when a month has a low ambient temperature, it will lead to the large temperature difference (ΔT) between inside flowing hot water and outside ambient temperatures. This ΔT directly corresponds to the heat energy losses due to conduction phenomena through the pipe wall. Hence, the higher ΔT value would result in the increase of heat energy loss through pipeline wall and vice versa.

In summary, better the pipeline insulation effect, the higher reduction in backup fuel consumption. This trend is true for all months except June and Aug. The reason behind the violation of the trend occurred in June and Aug is, as the number of hours period for which the auxiliary backup heater should remain turned on is smaller compared to that of May and July. The analysis of backup fuel savings shows that June has the smallest percentage of tubing insulation effect regarding natural gas fuel savings while Jan achieved the highest savings value. Overall possible monthly natural gas fuel savings as a result of the installation of a hybrid

Table 4
Water tubing insulation effect regarding percentage backup (gas) fuel savings.

Month	Percentage of backup fuel savings	Month	Percentage of backup fuel savings	Month	Percentage of backup fuel savings
January	43.88%	May	38.19%	September	40.81%
February	43.65%	June	41.36%	October	42.03%
March	42.47%	July	38.60%	November	42.80%
April	41.82%	August	41.44%	December	42.86%

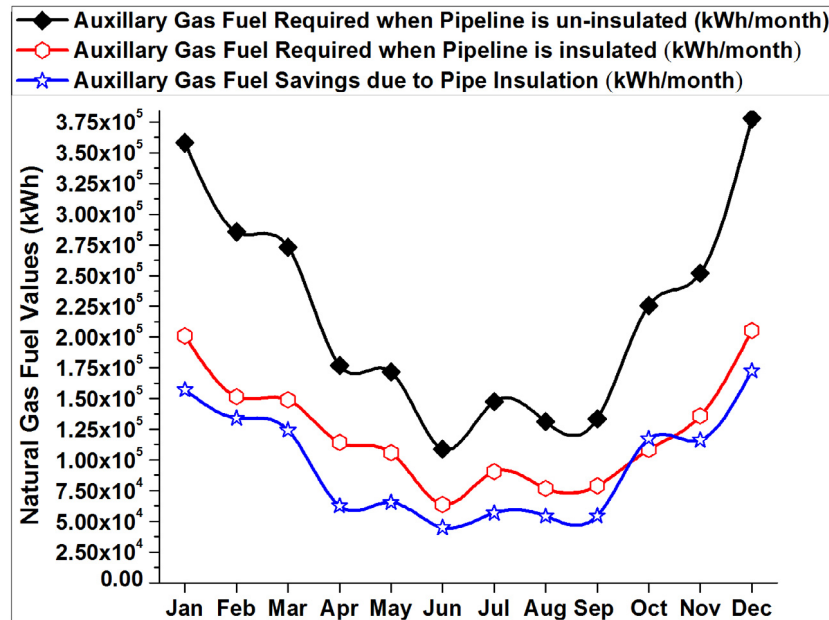


Fig. 10. Effect of water tubing insulation regarding backup (gas) fuel savings.

ETSWH system having 2 mm PVC water tubing insulation lie in $4.5 \times 10^4 - 1.7 \times 10^5$ kWh ($\sim 153.4 - 587.99$ mmBTU) range. Moreover, the total possible annual natural gas fuel savings value is 1.16×10^6 kWh ($\sim 3.954 \times 10^3$ mmBTU) as result of 2 mm PVC water tubing insulated hybrid ETSWH system installation, which is 31.89% greater than the savings value that can be achieved through ETSWH system without tubing insulation.

4.2.4. Differential temperature controller presence effect on hybrid ETSWH system's performance

The differential temperature controller can increase the operating efficiency of the heating systems. It controls the water circulation system based on temperature difference between the storage tank and the solar thermal collector. It also monitors the temperature of water delivered at user end by checking the set point temperature along with the upper and lower dead bands. Fig. 11 shows that the monthly backup (natural gas) fuel savings possible to be achieved through the insertion of a differential temperature controller in hybrid ETSWH system lies in $3.2 \times 10^3 - 2.0 \times 10^4$ kWh ($\sim 10.99-69.32$ mmBTU) range. The total possible annual natural gas fuel savings value is 9.9×10^4 kWh (~ 338.399 mmBTU) as result of the insertion of a differential temperature controller in a hybrid ETSWH system. The controller can avoid the problems of overheating and freezing in pipes. The percentage monthly backup (natural gas) fuel savings are mentioned in Table 5.

The percentage savings value due to temperature controller presence is smaller during a month for which the requirement of auxiliary backup (natural gas) fuel is less and vice versa. Higher the demand of auxiliary backup (gas) fuel, greater would be the effect caused by the presence of differential temperature controller.

4.2.5. Collector's plane area variations effect on hybrid ETSWH system's performance

Collector's plane area corresponds to the surface of solar thermal collector facing the incident solar radiations, where solar radiations are absorbed initially. Nominalization of solar collector's plane area affects the SWH system technically as well as economically. The collector's plane area affects the hybrid ETSWH system's performance.

Fig. 12 Shows the collector's annually harnessed useful energy and the resulted backup (natural gas) fuel savings. The analysis shows that there is a sharp increase at the start of the rising curve elaborating annual ETC useful energy then the rising curve gradually becomes almost steady. The percentage increase in ETC harnessed useful energy at each step of the rising curve (from 1 to 2.9 m^2) concerning predecessor area point is tabulated in Table 6.

The falling curve represents the auxiliary natural gas fuel required by hybrid ETSWH to fulfill hot water demand, and the corresponding percentage figures are mentioned in Table 6.

The results generated by the analysis reveals that when the collector's plane area is increased, the percentage increase in collector's useful energy at each area point concerning predecessor area point is decreasing. A similar trend can be observed for the falling curve elaborating the hybrid ETSWH system's backup (gas) fuel requirement. As the area of the collector increases, the useful energy harnessed value also increases. This increase is very sharp from starting to 1.7 m^2 area point; then the rising curve becomes gradually steady. It is because, after a certain area value, the further increase in the area corresponds to the increase in harnessed useful energy value but technically and economically does not make such design feasible.

Table 5
Percentage monthly backup (gas) fuel savings due to the presence of a differential temperature controller.

Month	Percentage of backup fuel savings	Month	Percentage of backup fuel savings	Month	Percentage of backup fuel savings
January	9.19%	May	3.18%	September	4.17%
February	8.69%	June	6.88%	October	4.63%
March	5.15%	July	5.01%	November	6.80%
April	3.46%	August	5.80%	December	8.01%

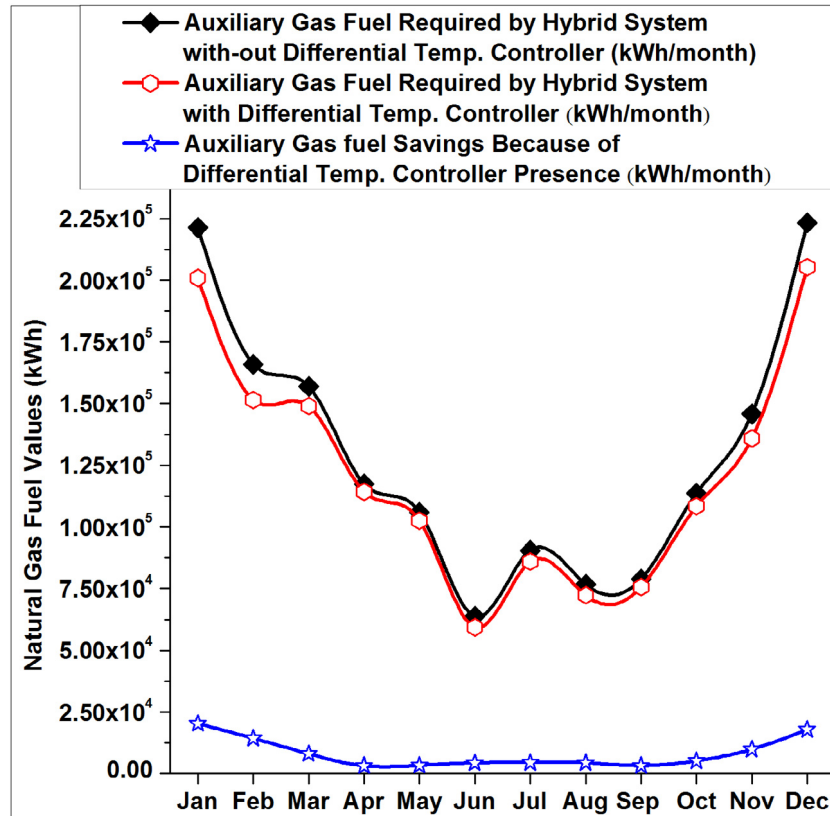


Fig. 11. The backup fuel savings possible to be achieved by having a differential temperature controller in ETSWH system.

Table 6
Effect of collector's plane area variations on regarding increased ETC harnessed useful energy and decrease in gas fuel requirement at each collector's plane area point w.r.t predecessor area point.

Month	Percentage increase in ETC useful energy harnessed at each increased collector's plane area point w.r.t predecessor area point (%)	Percentage decrease in backup fuel required at each increased collector's plane area point w.r.t predecessor area point (%)
1–1.3	24.92	3.67%
1.3–1.5	12.26	2.30%
1.5–1.7	10.26	2.28%
1.7–1.9	8.80	2.10%
1.9–2.1	7.47	1.98%
2.1–2.3	6.56	1.95%
2.3–2.5	5.67	1.69%
2.5–2.7	5.08	1.60%
2.7–2.9	4.46	1.44%

4.2.6. Hybrid ETSWH system performance comparison against hybrid FPSWH system

Comparative analysis of the performance of hybrid ETSWH and hybrid FPSWH systems is shown in Fig. 13. The comparative analysis is conducted considering useful energy harnessed by solar thermal ETC/FPC and backup (gas) fuel required by the system to fulfill the demand for desired hot water. The analysis shows that useful energy values harnessed by ETC (lie in 1.81 – 4.87 × 10⁵ kWh range) are higher than the harnessed useful

energy values of FPC (lie in 8.9 × 10⁴ – 2.88 × 10⁵ kWh range), tabulated in Table 7.

Consequently, the amount of backup (natural gas) fuel required by hybrid FPSWH system to fulfill the demand of hot water exceeds than that is required by the hybrid ETSWH system, a percentage exceeded values are mentioned in Table 7.

The result reveals that the amount of backup fuel required by hybrid FPSWH system is higher than that of hybrid ETSWH

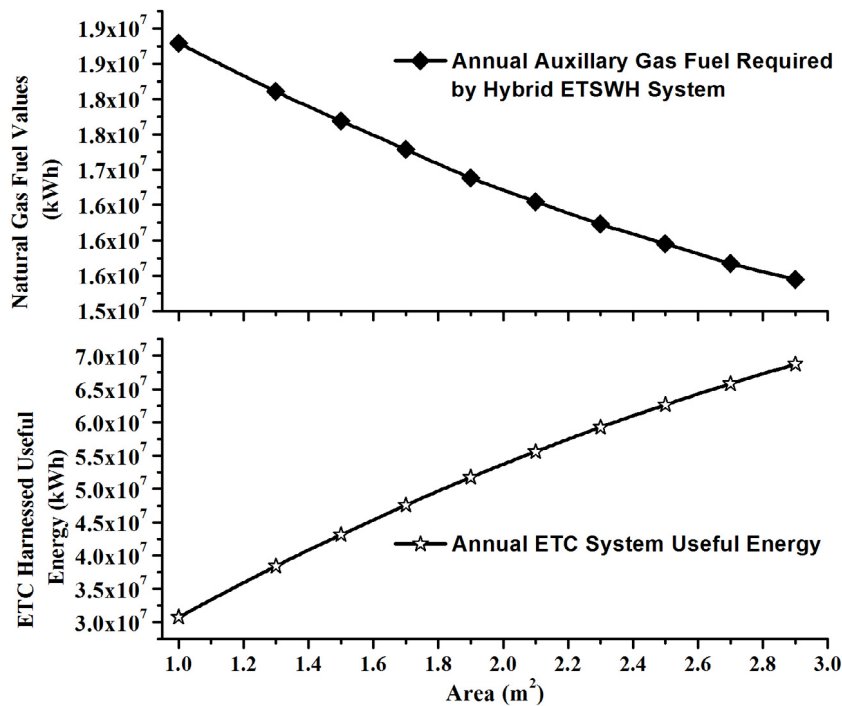


Fig. 12. Collector's plane area variations effect on hybrid ETSWH system performance regarding backup fuel required, ETC harnessed useful energy values.

Table 7

Performance comparison of hybrid ETSWH and hybrid FPSWH systems regarding higher harnessed energy value by the collector and percentage exceeded amount of backup gas fuel required.

Month	Percentage higher harnessed useful energy value by ETC, in comparison with FPC, harnessed useful energy value (%)	Percentage exceeded the amount of backup fuel value required by hybrid FPSWH, in comparison with hybrid ETSWH (%)
January	50.72	18.11
February	47.97	19.12
March	45.75	24.88
April	42.95	27.82
May	40.89	31.01
June	39.62	51.65
July	40.78	41.27
August	40.12	46.53
September	39.74	44.56
October	41.42	30.54
November	46.33	23.42
December	48.63	19.67

system in accordance with the harnessed useful energy gap between ETC and FPC: as much higher is the percentage value of useful energy harnessed by ETC more than FPC, as much smaller would be the backup fuel requirement value of hybrid ETSWH system compared to hybrid FPSWH system. Month-wise amount of backup (natural gas) fuel required by hybrid ETSWH system lie in $6.3 \times 10^4 - 2.0 \times 10^5$ kWh ($\sim 217.55-700.01$ mmBTU) range, while the monthly requirement of backup (natural gas) fuel for hybrid FPSWH to fulfill the desired hot water demand lie in $9.68 \times 10^4 - 2.37 \times 10^5$ kWh ($\sim 329.93-809.05$ mmBTU) range. Total annual amount of backup (natural gas) fuel required by a hybrid ETSWH system to fulfill the desired hot water demand is equivalent to 1.48×10^6 kWh (~ 5050.43 mmBTU), which is 26.67% less than the required annual amount of backup (natural gas) fuel for a hybrid FPSWH system equivalent to 1.88×10^6 kWh (~ 6397.45 mmBTU).

5. Financial analysis and environmental impact

Economic analysis portrays that either a certain project is viable to implement practically or not. The economic viability of a

project can be assessed through financial determinants like NPV, payback period, IRR, and BCR. NPV accounts for time value of earned money subsidized at discount rate value. IRR is rate value that makes the project present value equals to zero. NPV and IRR calculations can be represented by following relations 1 and 2 respectively (Brealey, 2012):

$$-CF_0 + \sum_{i=1}^t \left[\frac{CF_i}{(1+r)^i} \right] = NPV \quad (1)$$

$$-CF_0 + \sum_{i=1}^t \left[\frac{CF_i}{(1+r)^i} \right] = NPV = 0 \quad (2)$$

where; $i = 1, 2, 3, \dots, t$.

Payback period is an important financial parameter insight of an investor. It is simply cost of the project to the annual cash flows ratio. BCR is a ratio of the earned benefit to the invested money. For a project to be financially viable: BCR should be greater than one, and IRR value should be higher than discount rate value (Brealey, 2012).

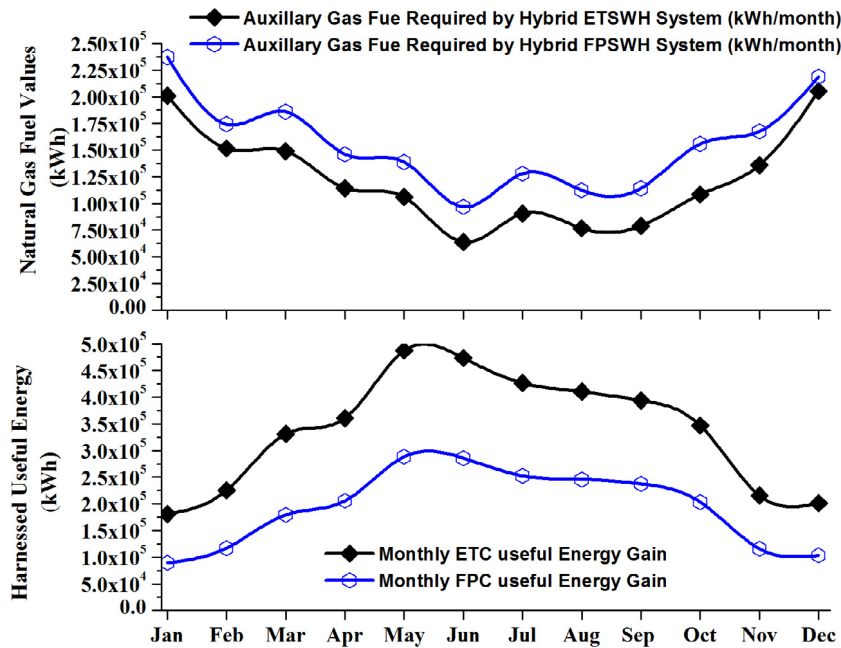


Fig. 13. The comparative performance analysis of hybrid ETSWH and hybrid FPSWH systems regarding useful energy harnessed and backup fuel requirement.

Comparative financial analysis of hybrid ETSWH and hybrid FPSWH in terms of NPV, IRR, payback period, and BCR shows that hybrid ETSWH system is financially more viable supported by all economic parameters with 26×10^3 NPV, 5.7 years payback period, 18.9% IRR value and 1.87 BCR value. While for hybrid FPSWH system: NPV is 19×10^3 (26.92% less than that of hybrid ETSWH), payback period equals to 6.4 years (12.28% greater than that of hybrid ETSWH), IRR equals to 16.6%, and BCR value is 1.64 (12.3% less than that of hybrid ETSWH). Additionally, developed hybrid solar thermal systems would lead to the appreciable amount of natural gas fuel savings that is another challenge on a path leading to sustainability and green environment.

Environmental pollution is one of the most concerned issues of the world and is a reason for the death of millions of people. That is why many protocols have been set to control GHG emissions that would result in a clean environment as well as financial benefits to the investor. Installation of a modeled ETSWH system would result in 8.79×10^5 kWh ($\sim 2.998 \times 10^3$ mmBTU) natural gas savings annually that would lead to 175.539 U.S.-tCO₂ emissions reduction. Moreover, the installation of a modeled FPSWH system would result in 6.45×10^5 kWh natural gas savings annually that would lead to 128.723 U.S.-tCO₂ emissions reduction. These reductions in GHG emissions can be claimed in terms of carbon credits, that would be another add-on towards increased economic viability.

The main reason for global acceptance and introduction of renewable energy systems is to solve issues associated with greenhouse gases that lead to global warming; this makes an environmental evaluation of solar energy technology very important. To save conventional energy sources and to protect the environment, renewable energy is the best aspect. A nonstop and noteworthy expansion of different technologies for using renewable energy sources is remarkable for the future of a stable global energy economy. As the demand for energy is increasing, the use of fossil fuel is also increasing, so only renewable energy sources can fill that gap between energy demand and use of fossil fuel. The need for healthy and hygienic food products, air-conditioning, hot water supply, stored horticulture product for a long time are such factors which encourage the use of renewable energy in industrial production and domestic process.

6. Conclusions and recommendations

A new hybrid TRNSYS model is developed for a solar water heating system using heat pipe evacuated tubes collector. The simulated model is validated through field trial data obtained from a system installed in Islamabad, Pakistan. Results concluded that there is 5~9% precision error between simulation outcomes and experimental field data values. Further, the performance of hybrid ETSWH system is evaluated considering different performance concerned parameters and concluded that:

- The modeled hybrid ETSWH can replace the conventional gas water heaters with 23%–56% possible backup conventional (natural gas) fuel savings annually.
- A 2 mm PVC water tubing insulation coating could result in 38%–44% conventional (natural gas) fuel savings.
- By installing a differential temperature controller, 2%–10% backup (natural gas) fuel savings could be achieved and additionally the threats of overheating and freezing in pipe phenomena will be minimized.
- ETC can harness 39%–51% more thermal radiant energy from incident solar radiations compared to FPC. Consequently, it leads to 18%–52% higher conventional (natural gas) fuel savings as a result of hybrid ETSWH system installation compared to that of the hybrid FPSWH system.
- Installation of a modeled hybrid ETSWH system and modeled hybrid FPSWH system would result, respectively, in 8.79×10^5 kWh and 6.45×10^5 kWh natural gas fuel savings annually that would lead to 175.539 U.S.-tCO₂ and 128.723 U.S.-tCO₂ emissions reduction, respectively.
- Additionally, developed hybrid ETSWH system is financially more viable compared to hybrid FPSWH system with 26.92% higher NPV, 12.28% less payback period, and 12.3% higher BCR value.

Moreover, the developed validated hybrid TRNSYS model and methodology used for the current study can be applied to other locations in the world for evaluating and comparing the performance of hybrid SWH systems during the design stage. Hence, the design of the validated hybrid model can be modified and improved before actual implementation.

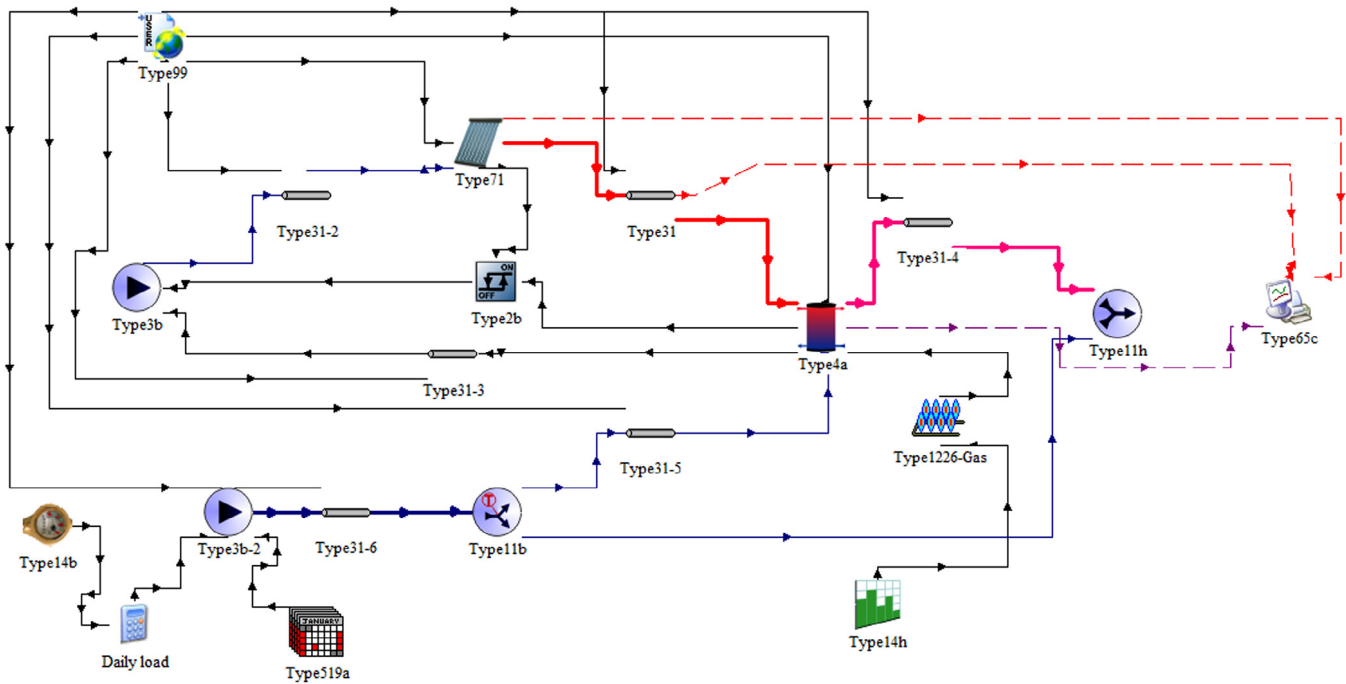


Fig. A.1. TRNSYS simulation model.

- Proposed hybrid system is need of time to avoid the inappropriate usage of natural gas for water heating purposes at such solar energy blessed land of the world (i.e. Pakistan). For this purpose, there is need to spread awareness in the society about solar thermal technologies to avoid natural gas fuel shortage in future.
- There should be a focus on manufacturing solar thermal collectors within the country rather than importing only, that will make this technology economically more viable.

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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Appendix

See Fig. A.1.

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