Development, Performance Investigation and Optimization of Solar Water Heater Hybridized with Conventional Fuel

By

Aamir Mehmood

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Supervised by

Asst. Prof. Dr. Adeel Waqas

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Center for Energy Systems (CES)

National University of Sciences and Technology (NUST)

H-12, Islamabad 44000, Pakistan

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CERTIFICATE

This is to certify that work in this thesis has been carried out by **Mr. Aamir Mehmood** and completed under my supervision in solar thermal laboratory, Centre for Energy Systems, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor: ______________

Dr. Adeel Waqas
Centre for Energy Systems
NUST, Islamabad

GEC member # 1: ______________

Dr. Majid Ali
Centre for Energy Systems
NUST, Islamabad

GEC member # 2: ______________

Engr. Waqas Khalid
School of Mechanical and
Manufacturing Engineering
NUST, Islamabad

GEC member # 3: ______________

Engr. Shahid Hussain Ansari
Centre for Energy Systems
NUST, Islamabad

HoD-CES ______________

Dr. Zuhair S. Khan
Centre for Energy Systems
NUST, Islamabad

Principal/ Dean ______________

Dr. M. Bilal Khan
Centre for Energy Systems
NUST, Islamabad

DEDICATION

To my loving parents, elder brother and kind teachers.

ABSTRACT

Renewable energy resources utilization can address the both most emerging issues of the world in current era: rapid depletion of conventional fossil fuels reserves and drastic climate changes. The main theme of this work is analytical and experimental performance investigation of solar water heating (SWH) technology for Pakistan, a country facing disastrous power and gas shortfalls. For this purpose, a SWH system is designed for domestic sector of Pakistan using weather information of a location having latitude= 33.6^{o}N and longitude= 73.1^{o}E. Designed solar water heater in hybridized with conventional fuel using auxiliary fuel heater to provide backup for non-sunny time.

Designed hybrid SWH system is modelled in TRNSYS simulation program using evacuated tube and flat plate collectors. Performance of hybrid evacuated tube solar water heating (ETSWH) system is evaluated and compared for winter season with gas water heating system. It is concluded that replacement of gas water heating system with hybrid ETSWH system would result in 23-42% seasonal natural gas fuel savings. Effect of water pipeline insulation and differential temperature controller presence is also investigated in terms of natural gas fuel savings. Performance of hybrid ETSWH system is compared with hybrid flat plate solar water heating (FPSWH) system and found that hybrid ETSWH system is much more efficient than FPSWH system. Comparative economic viability of hybrid ETSWH and hybrid FPSWH systems is analyzed in terms of net present value, internal rate of return, payback period and benefit-cost ratio. It is concluded that hybrid ETSWH system is more economical with ~5.7years payback period based on the savings achieved through reduced consumption of natural gas fuel. Environmental analysis is also performed in terms of greenhouse gases emissions reduction as result of hybrid SWH system application. Experimental setup mainly consists of heat pipe evacuated tube collector and multi-fuel furnace is developed and experimentation is performed providing natural gas as backup fuel. Percentage error between experimental and analytical results found equals to 5-6%. Performance of hybrid SWH system is optimized through MATLAB m-file mathematical modelling by determining the optimum tilt angle of south facing solar thermal collector, equals to Lat.+19^{o} for winter season in capital city of Pakistan.

Keywords: Solar water heater, TRNSYS, Tilt angle, Natural gas, Useful energy

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* Aamir Mehmood, Adeel Waqas, Hafiza Tahira Mahmood, “Performance of Heat Pipe Evacuated Tube Solar Water Heater Hybridized with Natural Gas Fuel”, [J] ASME Journal of Solar Energy Engineering (Under-review)

** Aamir Mehmood, Adeel Waqas, Waqas Khalid, “Techno-economic Evaluation of Flat Plate Solar Collector for Domestic Water Heating Application in Different Climates: A Comparative Study for Pakistan”, [J] Solar Energy Journal (Under-review)

*Attached as Annexure I

**Attached as Annexure II

LIST OF ABBREVIATIONS

AF	Air-fuel
BCR	Benefit-cost ratio
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
NPV	Net present value
IRR	Internal rate of return
SWH	Solar water heater/heating

NOMENCLATURE

A_c	Absorber/aperture surface area of solar collector (m^2)
A_{edge}	Collector edge area (m^2)
C_b	Bond conductance (W/m ^oC)
C_p	Specific heat capacity of circulating fluid (J/kg ^oC)
D	Collector tube diameter (inside) (m)
F_R	Collector heat removal factor
F'	Collector Efficiency factor
F''	Collector flow factor
G_{sc}	Solar constant (W/m^2)
h_{fi}	Heat transfer coefficient inside tube (W/m^2 ^oC)
h_w	Wind heat transfer coefficient (W/m^2 ^oC)
I	Hourly global radiation on horizontal surface (W/m^2)
I_b	Beam component of incident solar radiations (W/m^2)
I_d	Diffused component of incident solar radiations (W/m^2)
I_o	Hourly extraterrestrial radiations (W/m^2)
I_T	Available solar radiations on sloped surface (W/m^2)
k	Insulation conductivity (W/m ^oC)
k_T	Hourly clearness index
L_b	Back insulation thickness (m)
L_e	Edge insulation thickness (m)
L_t	Collector tube sheet thickness (m)
$\dot{m}$	Circulated fluid mass flow rate (kg/s)
n	Number of days
N	Number of glass covers
Q_u	Useful energy gain of collector (J)
q_u	Useful energy gain per unit collector area (J/m^2)
R_b	Ratio of beam radiation on titled surface to that of horizontal surface

S Absorbed solar radiation (W/m^2)

T_a Ambient temperature (^oC)

T_{fi} Fluid temperature at solar collector entrance ((^oC))

T_{fo} Fluid temperature at solar collector exit ((^oC))

T_{pm} Mean temperature of absorber plate ((^oC))

U_b Collector back loss coefficient ($W/m^2\ ^oC$)

U_e Collector edge loss coefficient ($W/m^2\ ^oC$)

U_L Collector overall heat loss coefficient ($W/m^2\ ^oC$)

U_t Collector top loss coefficient ($W/m^2\ ^oC$)

W Distance between collector tubes (m)

Greek Letters:

α Absorptance

β Slope angle of collector

ε_g Emittance of glass

ε_p Emittance of plate

δ Declination angle

η Collector efficiency

ϕ Latitude of location

θ Angle of incidence

θ_z Zenith angle

σ Boltzmann constant

ς_g Albido (Reflectivity of ground)

τ Transmittance

ω Hour angle

Subscriptions:

b Beam radiation

d Diffuse radiation

g Ground reflected radiation

av Average

Chapter 1

INTRODUCTION

1.1 General Background

Energy sector occupies the backbone position in today's era of technology and economic war. In present world of science and technology where every country is struggling for its nation's sustainable development and to be a part of developed countries, world is heading towards globalization. Due to cultural exchanges as result of expanded urbanization and industrial revolution, global primary energy demand is continuously increasing in an impressive way and has become almost double during last ~3decades [1]. To fulfill this exponentially increasing energy thirst, conventional fuels are being consumed extensively and are combusted in different proportions as: liquefied petroleum products-33.7%, coal-30.5% and natural gas-24.4% [2, 3]. This extensive combustion of high carbon content fossil fuels emerged two main world's concerns: rapid depletion of fossil fuel reserves and climate changes. It is reported that crude oil and natural gas reserves would run out of this world by ~2052 and ~2073 respectively if fossil fuels consumption remained continue at current rate [3, 4]. Climate changes caused by GHG emissions resulted in death of ~1.6 million people reported by World Health Organization (WHO) and this number is expected to become double by 2020 [5, 6]. These emerging threats forced the world to divert its focus from fossil fuel technologies towards renewable and clean energy systems and this was the main motivation quiescent behind selecting current research topic.

Nature has gifted this world with several abundant and non-replenish-able sources of energy that are large enough to accomplish current overall energy requirements. Although it is proven that renewable energy technologies couldn't replace the fossil fuel technologies but can serve as an add on and can play appreciable role in improving the energy security and to mitigate environmental concerns. Renewable energy proportion in global energy mix is continued to increase and has already surpassed the targets in 2010 that were project for 2020 [7]. Renewable energy share of global final energy consumption estimated at end of 2013 was 22.1%, that was 3.1% greater than that of 2012 [7] and is continued to increase significantly.

Among renewable energy technologies, solar seems the more promising one has yearly increased usage rate of ~30% since 1980 [8]. Solar technology has two main usage domains: solar thermal heating/cooling and solar photovoltaic. The economic benefits possible to be attained as result of SWH technology application can be realized through conventional fuel savings achieved and reduction in environmental issues. SWH systems are playing a significant role in domestic and industrial sectors of many countries by saving their conventional fuels being used for water heating purpose. Total globally installed SWH capacity has increased by 70% and 13.5% in 2013 from 2004 and 2012 respectively [7]. China is the leader of global solar thermal market [7] while Pakistan is far behind in solar applications instead of having much more solar potential than China that can be harnessed. Solar radiation map of Pakistan is shown in Figure 1.1 [9].

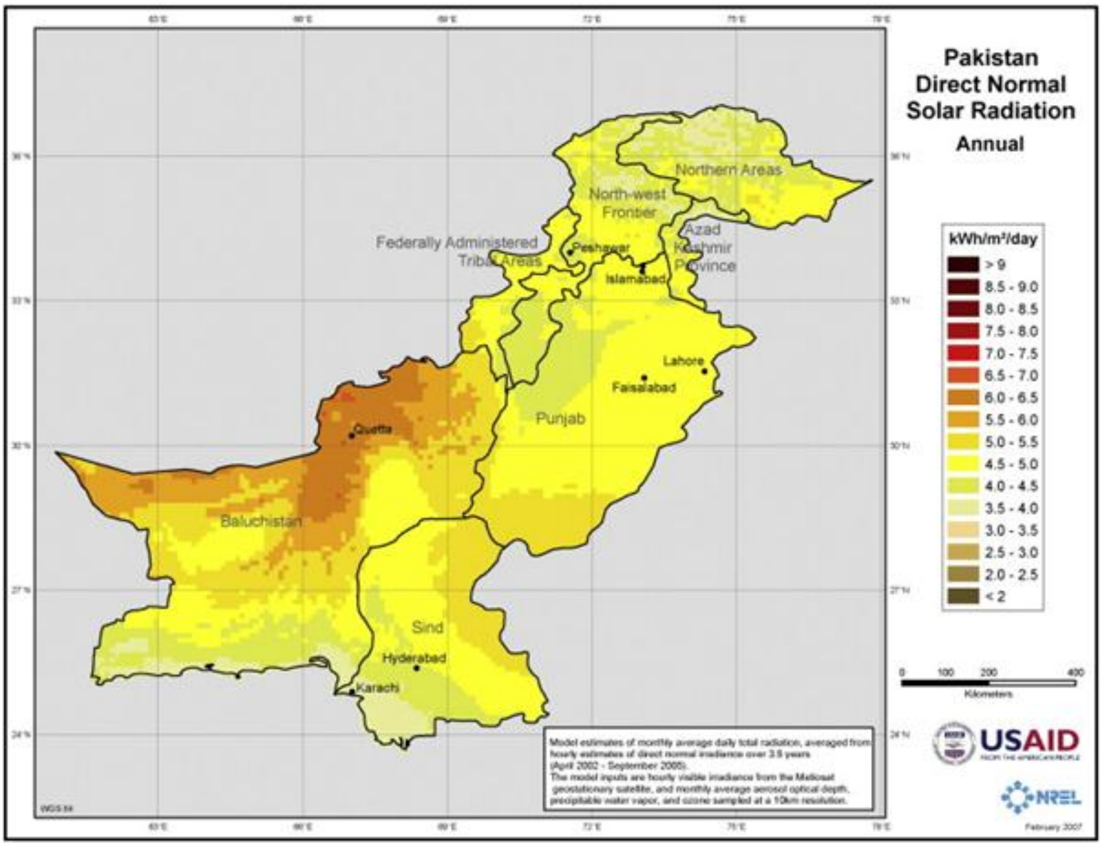

Figure 1.1: Solar radiation map of Pakistan

1.2 Research Questions

The main questions addressed in current work are:

- How much conventional fuel could be saved through application of developed hybrid SWH system?
- What is the effect of water pipeline insolation and differential temperature controller presence in terms of possible conventional fuel savings as indication parameter?
- Economics of modelled system is analysed and find out which solar collector among ETC and FPC is more viable economically?
- What is the tilt angle of non-concentrated solar thermal collector at which performance of SWH system would be optimized?
- It is also addressed that which conventional fuel among natural gas and wood is better to use as backup fuel for water heating purpose?
- It is also evaluated that how much percentage error exists between an ideal and real system through comparative investigation of analytical and experimental results?

1.3 Study Objectives

The overall broad objective of this work is to develop and study the thermal and economic behavior of SWH system hybridized with conventional fuel.

Explicitly the current study is focused to achieve the following objectives:

i. Design and development of hybrid SWH system that could result in reduced conventional fuel's consumption.
ii. Performance evaluation of hybrid SWH system in comparison with natural gas water heating system considering fuel consumption as performance parameter.
iii. Comparative study of thermal, economic and environmental behavior of ETSWH and FPSWH systems.
iv. Non-concentrated solar thermal collector's tilt angel based performance optimization of hybrid SWH system.

Keeping in view these objectives, a SWH system is developed that will replace the conventional fuel being consumed for water heating purpose with solar thermal energy. To provide continued hot water supply, developed SWH system is hybridized with conventional fuel using multi-fuel furnace that could be run on natural gas or wood biomass fuel. TRNSYS simulation model based numerical and experimental performance is investigated. Performance of SWH system is optimized considering solar thermal collector's tilt angle as affecting parameter using MATLAB m-file user interface, because tilt angle of solar collector is the most focusing perspective regarding its performance.

1.4 Scope and Limitations of Study

This work comprises of theoretical, simulation and experimental observations. The scope and limitations of the study are:

- For simulation work, climatic data of Islamabad, capital city of Pakistan, is taken having latitude= 33.6^{o}N and longitude= 73.1^{o}E where summer season is almost dry and hot while winter season is very cold.
- Weather data used for simulation work is taken from meteonorm database. And the performance of hybrid SWH system modelled in TRNSYS software is evaluated for winter season (October to April).
- TANSYS simulation based performance of both ETC and FPC is evaluated, but the experimental work is carried out only with ETC.
- Tilt angel based performance optimization is carried out considering useful energy produced by non-concentrated solar thermal collector (FPC/ETC) as indication parameter.
- During experimentation, fuel combusted in multi-fuel furnace for water heating is recorded only. Emissions and fuel wastage due to other losses are not considered due available facilities limitations.

1.5 Methodology Adopted for the Current Study

The methodology adopted for this research work (shown in Figure 1.2) starts from a very initial step of topic selection. After selecting work domain, literature of the topic is searched out for understanding background of constituent parts of work and to understand that what and how I have to do something distinguishing in selected domain? Then a SWH system hybridized with conventional fuel using natural gas heater is simulated in TRNSYS software and its thermal performance is evaluated. The economic behavior of TRNSYS modelled hybrid SWH system is analyzed through RETScreen simulation program. After analytical study of designed system, model is developed and experimentation is performed. Percentage error between analytical output and experimental results is found and performance of hybrid SWH system is optimized based on solar collector's tilt angle through MATLAB numerical modelling. Finally, the work is concluded with dissertation write-up along with simulation and experimental results based articles.

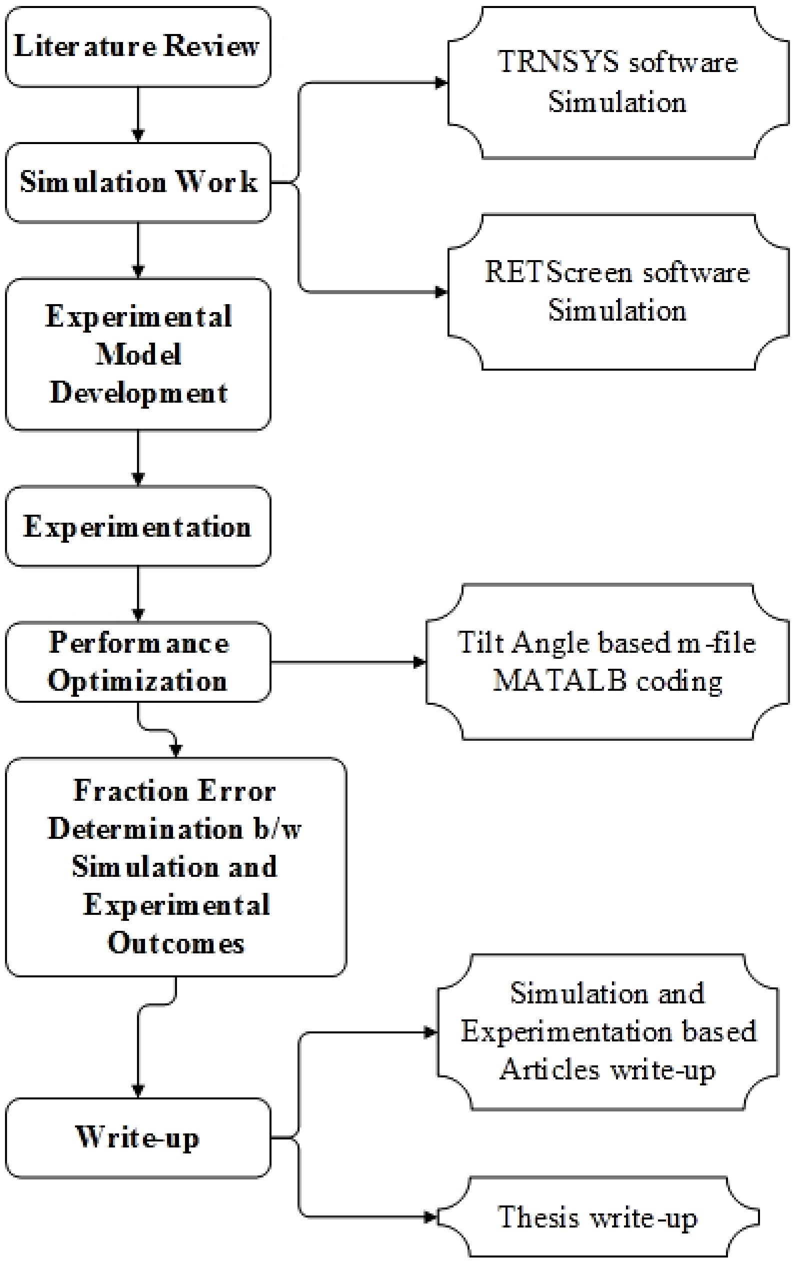

Figure 1.2: Work methodology adopted for current study

1.6 Dissertation Organization

This complete write-up is segregated into six main sections, as:

Chapter 1 gives the answers of initial pre-requisites required for starting research work i.e. motivation, what to do in this work, objectives of work and methodology adopted for current study.

Chapter 2 covers literature review starting from very initial point 'solar energy utilization' and describes background of system parts i.e. solar water heating, solar thermal collectors and optimization of SWH system.

Chapter 3 is concerned about simulation work performed to study the technical viability of hybrid SWH system using TRNSYS simulation program. RETScreen software simulation is introduced for system's economic study. Solar collector's tilt angle based performance optimization of SWH system is also carried out through MATLAB numerical m-file coding.

Chapter 4 explains the experimentation phase involving experimental set-up designing, manufacturing and tests being performed to investigate the developed hybrid SWH system.

Chapter 5 discusses the all results obtained during simulation and experimental phases and comparison is performed to figure out the percentage error between simulation and experimental results.

Chapter 6 concludes the work outcomes and elaborates possible future perspectives of current work.

Summary

This chapter introduces about initial pre-requisites required for starting research work i.e. motivation, what to do in this work, objectives to be achieved and work methodology adopted for current study. The following chapter is concerned about the literature study of constituent parts of system to be developed and studied in current work.

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Chapter 2

LITERATURE REVIEW

2.1 Solar Energy Utilization

Sun light is the most important sustainable energy source in our universe having an indefinite life time and zero negative environmental impact. It is fact that sun provides ~1500 million billion kWh per annum to the world which is 10,000 times more than the energy needed by human race at present [1]. This indefinite solar potential can be harnessed in four technological ways (as shown in Figure 2.1) [1, 2]:

- Chemical Process: In which solar energy is used to convert CO_2 to O_2 through photosynthesis.
- Electrical Process: Involves conversion of solar irradiance energy into electrical energy directly using photovoltaic converters.
- Thermal Process: In which solar irradiance energy is converted into heat energy using solar thermal phenomena.
- Mechanical Conversion**:** Conversion of solar radioactive energy into mechanical as wind and water streams.

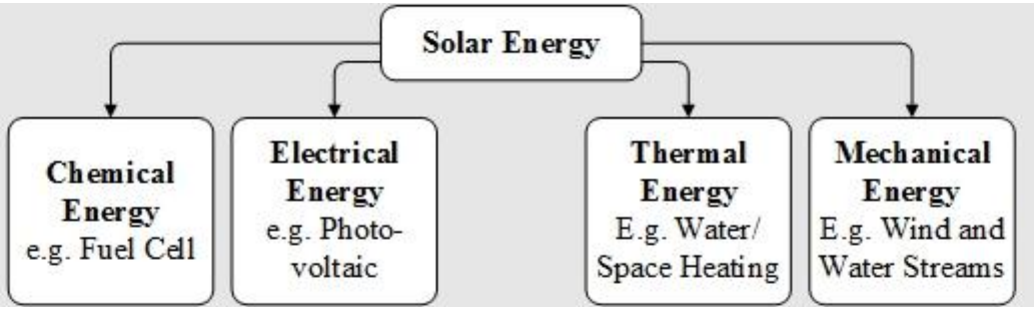


Figure 2.1: Solar energy conversion to other energy forms [1, 2]

Among these, solar thermal phenomenon applies different procedures for capturing solar thermal heat energy used for water and space heating applications. A specific procedure to be adopted for a solar thermal process depends upon temperature level required and corresponding amount of converted energy that could be achieved effectively [2].

The history of utilizing solar radiant energy goes way back to Ancient Greeks and Romans when the buildings were constructed in such a way that the sun rays provided light and heat for indoor spaces. Romans advanced their art of constructing the buildings by covering south facing openings with glass for retaining heat of winter sun [3]. With the passage of time, large developments in solar field have made the solar water heating technology much mature and cost effective ways of reducing natural gas and electricity consumption [4].

2.2 Solar Water Heating

Solar energy reaching the earth surface can be utilized in many ways like for electricity production, water and space heating applications. SWH is preferred for industrial and domestic sectors as SWH is well developed and proven technology. SWH technology got progress from a hypothesis to prototype stage in 1767 [5] when Swiss naturalist De Saussure built a “Hot Box” using a box with black painted surface. This black painted metal tank full of water was placed to absorb solar thermal energy for heating the inside flowing water. Disadvantage associated with this system was, even on clear sunny day it took much time for water to get hot usually from morning to early afternoon. And after the sun being set down, tank rapidly lost the heat because of not being insulated [3]. This hot box was capable of being used for cooking purposes too.

In 19th century, SWH technology was not much popular and people used a stove being run on wood or coal for water heating purpose. In those days, fuels like wood, coal or gas couldn’t be easily accessed and hence these fuels were expensive [3, 6]. The first commercial SWH called as “Climax” was designed and patented by Clarence M. Kemp in 1891 [3, 4]. He placed a metal tank within wooden box covered by transparent glass cover. Built system produced hot water of 38.8^{o}C on sunny day. This was an alternate to expensive fossil fuels and burning wood for water heating purpose.

In 20th century beginning, scientists designed many improved systems to make SWH technology durable and efficient but still heating and storage units were combined and were exposed to weather and cold nights. As result of these struggles in design improvement, thermosyphon principle was introduced for the first time by William

Bailey in 1909 [4, 7]. William Bailey modelled and started selling SWHs consisted of indoor water storage tank and separate outdoor solar thermal collector where hot water was allowed to circulate through natural convection [6, 8]. After that, for the first time a simple SWH consists of a basin having top covered by glass was modelled in Japan by Yamamoto [7] in 1950 and more than 100,000 collectors of such type were in use by 1960s. In Australia this technology grew after increase in oil process twice [6]. In mid 1950s, Levi Yissar suggested to use solar thermal energy for domestic water heating purpose in Israel. In response, 60% of population started heating water using solar energy by 1983. Today more than 90% of Israeli households own SWHs [4, 6].

Up to 1930s, coal fired boilers were mainly used for domestic water and space heating applications [9]. First commercial SWH became in market in early 1960s, was of thermosyphon type having flat plate collector type absorber area of 3-4m^2 to energize 150-180Lit storage tank capacity [7]. In mid 1970s, Greece also started taking interest in SWH technology after first solar collector being imported from Israel and SWH industry grew rapidly even Greece became the leader in Europe and stands 2nd in world for m^2 installed SWH systems per capita [6, 10]. SWH technology grew exponentially in first decade of 21st century in the whole world (as shown in Figure 2.2) and now China is leading in this technology with respect to its installation capacity and generation, the following countries among the list of top five are: United States, Germany, Turkey and Brazil [11].

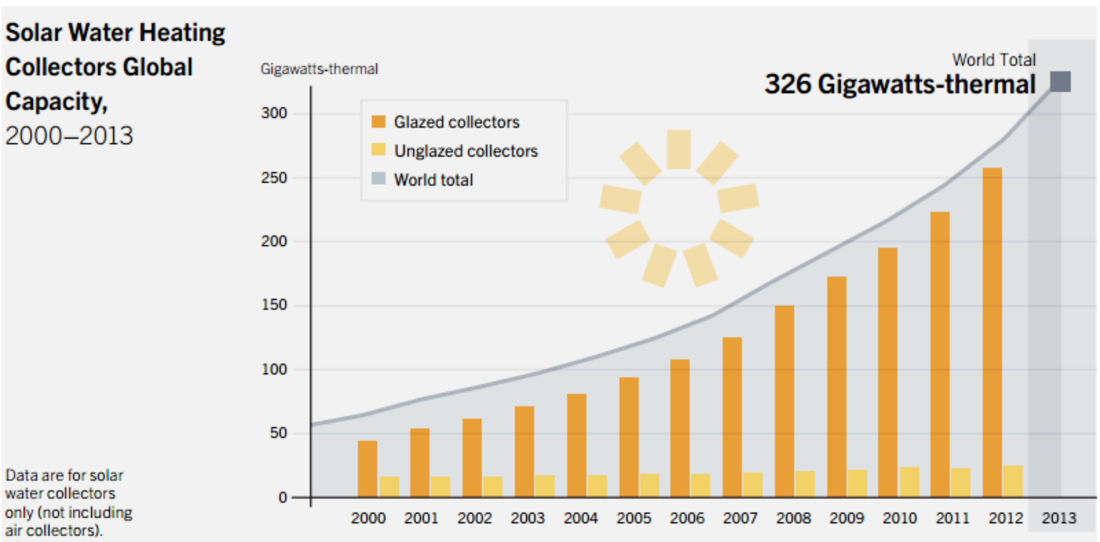


Figure 2.2: Global solar water heating technology growth during 2000-2013 [11]

2.2.1 Types of Solar Water Heating Systems

SWH systems are classified into two types on the basis of water circulation mechanism: active and passive. Main difference between these two water circulating systems is of requirement of pump power for circulating hot water between solar collector and storage tank.

- **Passive Solar Water Heating System**

Passive SWHs are of two types [12, 13]: batch system and thermosyphon type water heaters. These systems work on natural circulation flow mechanism in which tank is placed above the solar thermal collector and hot water is circulated between collector and storage tank as function of density difference. Flow rate of circulating water is function of useful energy gain of solar thermal collector [12] that warms up the collector's inside water and produces temperature difference between collector's incoming cold and outgoing hot water. General working schematic of passive SWH is depicted in Figure 2.3.

There are two main approaches used for analysis of SWH systems having passive water circulation mechanism, proposed by Close (1962) and Morrison and Braun (1985) [12]. Many scientists, i.e. Lof and Close (1967), Gupta and Garg (1968), Tabor (1969), Cooper (1973), Morrison and Sapaford (1983), [12] analyzed the performance of natural circulation mechanism in terms of water temperature rise from point of collector's inlet to outlet.

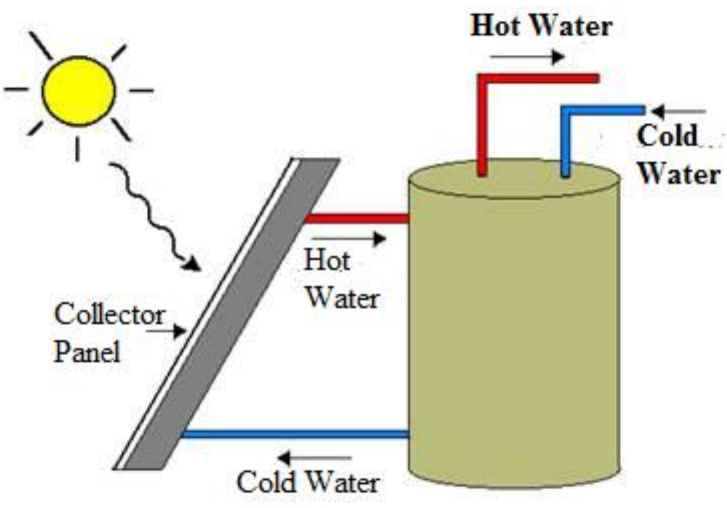


Figure 2.3: Passive solar water heating system [14]

- **Active Solar Water Heating System**

Active SWH systems (shown in Figure 2.4) [12] work using forced water circulation mechanism in which a pump is required, usually controlled by differential thermostat according to system's requirements. Differential controller turns on the pump when temperature of water at top of header becomes sufficient higher than of at bottom. A check value is also equipped to prevent the reverse flow of circulating fluid.

Active SWH systems have comparatively low flow rates and are referred for climates where freezing temperatures are frequently encountered. Domestic active SWH system sizing can be done using rule of thumb or by economic and thermal design and analysis procedures [12]. Buckles and Klein (1980) carried out a long term simulation based performance analysis of domestic SWH system working on forced circulation mechanism and concluded that effectiveness of solar collector's heat exchanger is an important design aspect [12].

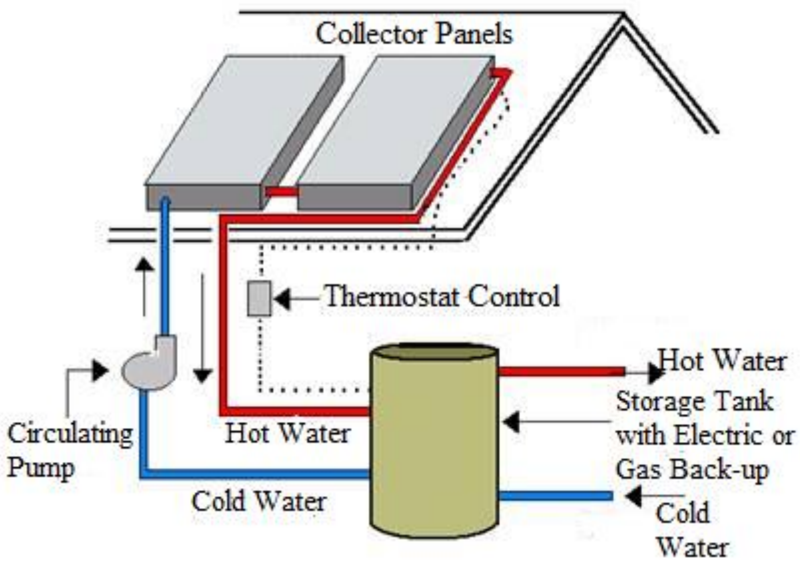


Figure 2.4: Active solar water heating system [14]

Active and passive SWH systems are further classified in to two types: direct and indirect SWH systems.

- **Direct Solar Water Heating System**

Direct SWH system also called as open loop system [13], in which water itself is heat transferring fluid and circulates through collector. These collectors provide little or no overheat and freezing protection, so that these systems are not appreciated for the climates where freezing temperature may occur.

- **Indirect Solar Water Heating System**

Indirect SWH system also known as closed loop system [13] that requires pump to circulate heat transferring fluid through collector and also heat exchanger where heat is transferred from working fluid to water, e.g. drain back and anti-freeze systems.

2.2.2 Solar Water Hating System Designs

SWH systems range from very simple (for hot and moderate climates) to fairly complex one (for cold climates) in design perspective:

- **Batch Solar Water Heating System**

The batch system or ICS (shown in Figure 2.5) [12] is the simplest and the most direct heirs of the first SWHs. It has no pump while anti-freezing agent is taken under consideration during its design construction. It combines the solar thermal collector and a storage tank into one single unit referred for regions having moderate climate.

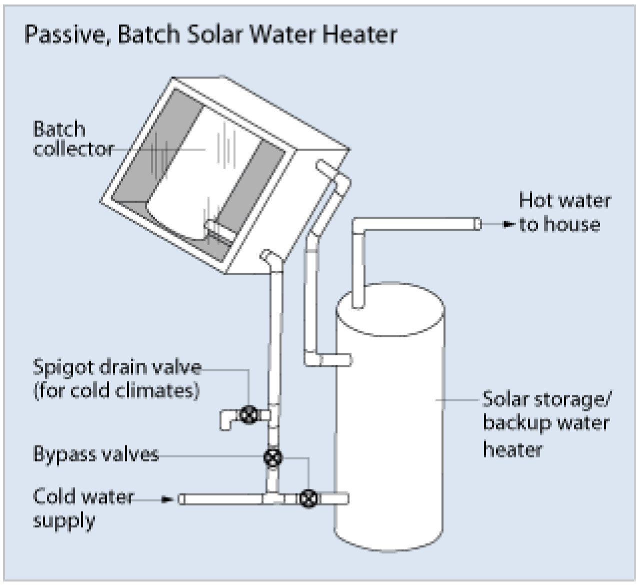


Figure 2.5: Batch solar water heating system [15]

- **Thermosyphon Solar Water Heating System**

Thermosyphon SWH systems (shown in Figure 2.6) are simple, very efficient and very popular in moderate and hot climates. They are cheap and don't include pumps or special controllers. They can be installed in colder climates when equipped with small circulating pumps (to circulate water and to prevent from freezing phenomena).

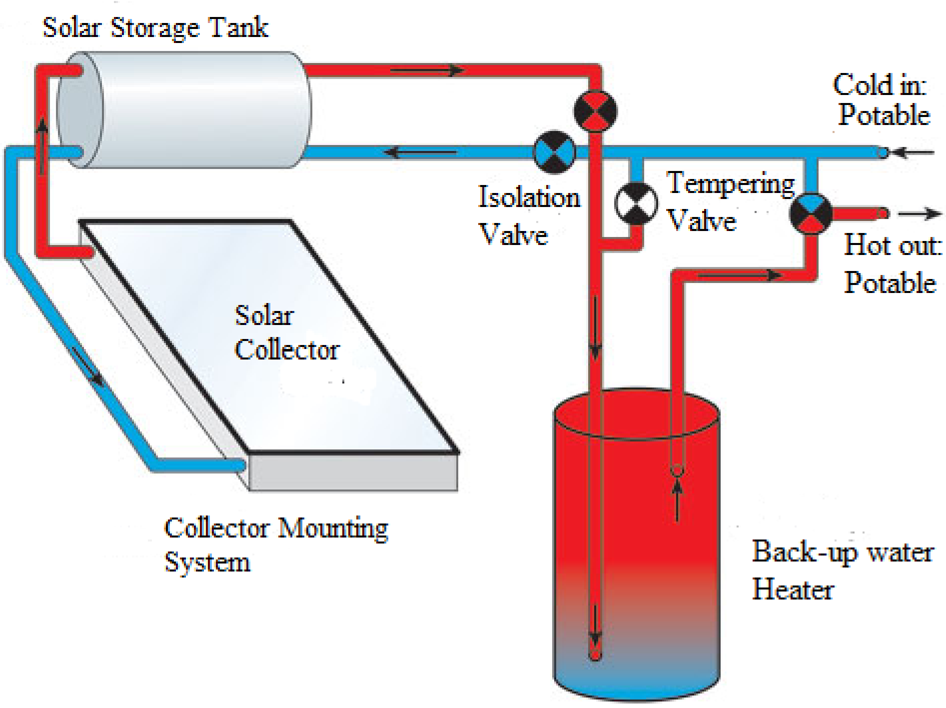


Figure 2.6: Thermosyphon solar water heating system [15]

- **Drain-back Solar Water Heating System**

Drain-back systems are preferred for cold climates for its relative simplicity and long lifespan. Typical drain-back SWH system (shown in Figure 2.7) is comprised of [12]:

- Solar thermal collector
- Controller
- Pump
- A large storage tank
- A small drain-back reservoir tank (say, 10 gallon/38 liters);
- Heat exchanger (usually internal to one of the tanks) and
- Temperature sensors and other minor accessories.

Modern drain-back systems use ETCs and distilled water or glycol anti-freezing mixture for heating the fluid and to avoid freezing phenomena.

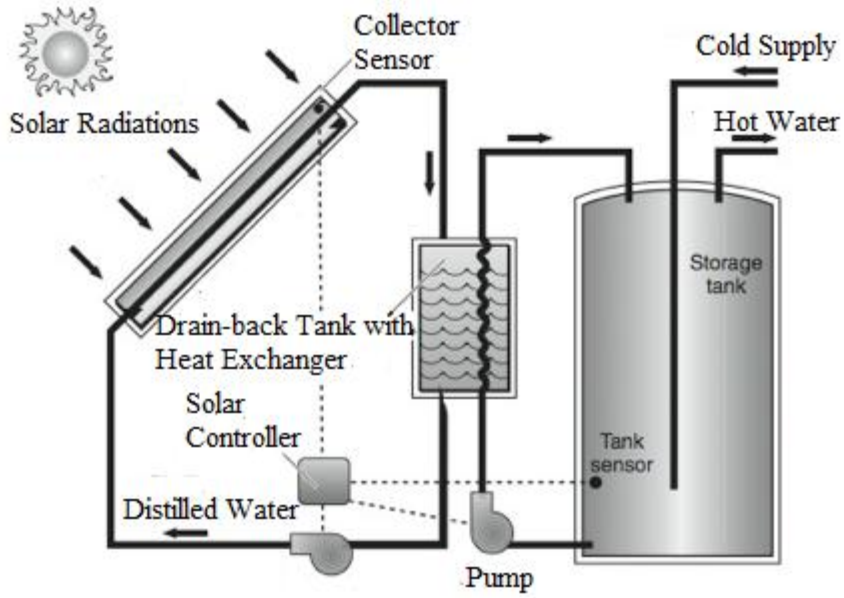


Figure 2.7: Drain-back solar water heating system [16]

2.3 Solar Water Heaters and Collectors

A functional solar generator has two key elements: a solar thermal collector and storage unit. Solar thermal collector is main key element of solar heating systems that captures solar radiations, converts into heat energy and transfers to working fluid flowing through it [17] that results in increasing the working fluid temperature.

2.3.1 Classification of Solar Thermal Collectors

On the basis of achievable temperature and thermal efficiency, solar thermal collectors are classified into four types [18] as shown in Table 2.1.

Table 2.1: Classification of solar thermal collectors based on achievable temperature range and efficiency

Solar Collector Type	Temperature Range (^{o}C)	Efficiency (%)
Flat Plate Collector	Up to 75	30-50
Evacuated Tube Collector	Up to 200	30-50
Parabolic Cylinder	150-500	50-70
Parabodial	1500 and more	60-75

Temperature of the working fluid that could be achieved possibly through certain solar thermal collector depends upon the solar radiations concentration level [12, 18]. On the basis of design models, solar thermal collectors are generally classified into stationary and concentrating types as shown in Figure 2.8. Each type of solar thermal collectors can further be classified on the basis of number of covers used to reduce the heat losses from top surface [12, 18].

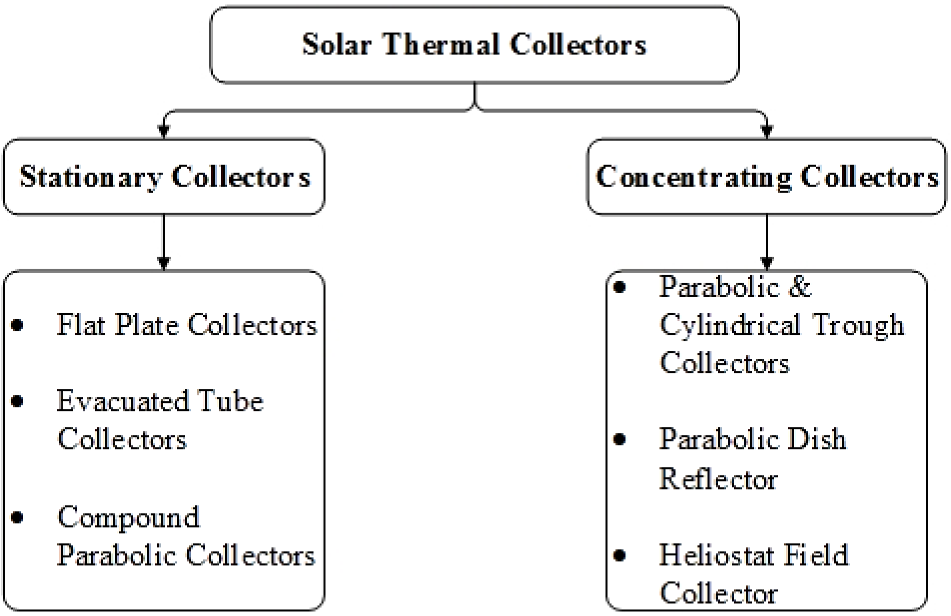


Figure 2.8: Classification of solar thermal collectors based on design models [19]

Maximum useful energy gain from solar thermal collector largely depends upon the angle at which solar radiations are striking on collector's surface. In that case there are three possible designs based on the position of solar thermal collector in relation to sun [18] as shown in Figure 2.9.

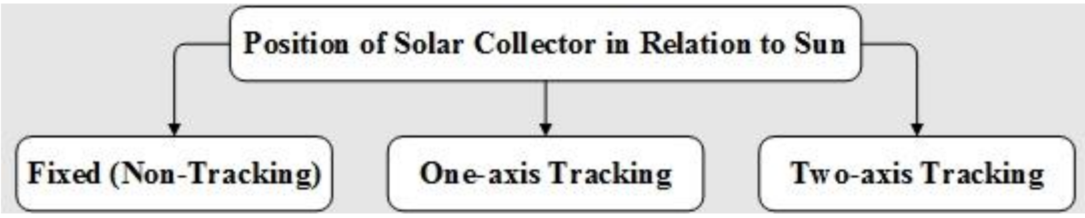


Figure 2.9: Solar thermal collector's classification based on relative position of collector and sun [18]

2.3.2 Stationary Solar Collectors

Stationary solar collectors (shown in Figure 2.10) [6] use either flat plate or parabolic reflectors for directing solar radiant energy to an absorber surface or aperture at wide acceptance angle.

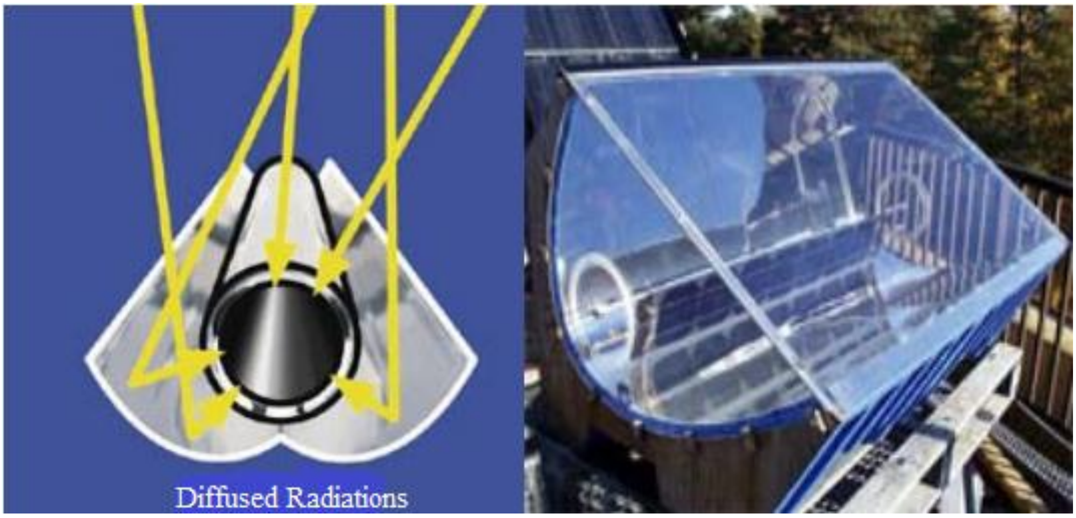


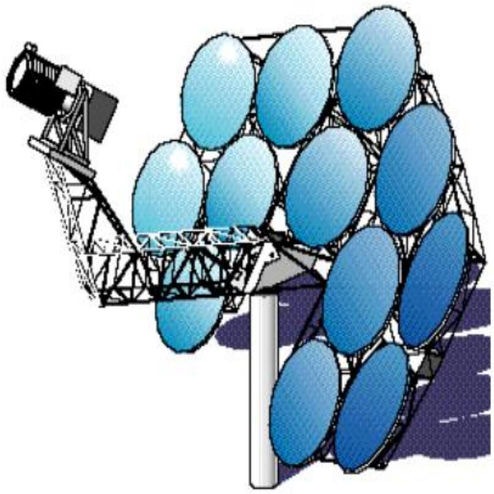
Figure 2.10: Stationary solar thermal collectors [6]

The acceptance angle is that one through which light source can be moved and connect at absorber surface [20]. The wide acceptance angle eliminates the need of sun tracker for these reflectors.

2.3.3 Concentrating Solar Collectors

In concentrating solar thermal collectors [21], solar radiant energy falling on a large area is focused on smaller area after converting into heat form. These collectors are used for attaining higher temperatures. Concentrating collectors can concentrate only direct sun's beams. So tracking system is requirement of concentrating solar collectors. Concentrating solar thermal collectors are used in different ways (as illustrated in Figure 2.11): central receiver system, parabolic troughs and parabolic dishes [21, 22].

(a) Central receiver system



(b) Parabolic dish collector

(c) Parabolic trough collectors

Figure 2.11: Concentrating solar thermal collectors [21, 22]

2.3.4 Flat Plate Collectors

FPCs are commonly used for domestic water and space heating applications. A flat plate solar thermal collector consists of three basic elements (as shown in Figure 2.12): transparent cover sheets, an absorber and insolated box.

The absorber is usually a metal sheet having much high thermal conductivity with integral or attached ducts or tubes. Absorber's surface is coated or painted to maximize the absorption of incident radiant heat energy and to minimize the radiant losses through emission. An insulated box provides the sealing and structure to collector and also helps in reducing the back surface heat energy losses of collector

[23]. Cover sheet at top of collector called as glazing allows the coming sunlight to pass through absorber surface and also performs the function of insulation for the space between absorber surface and glazing to prevent the cool air flow into space. Although glass cover also reflects back the small portion of incident sunlight.

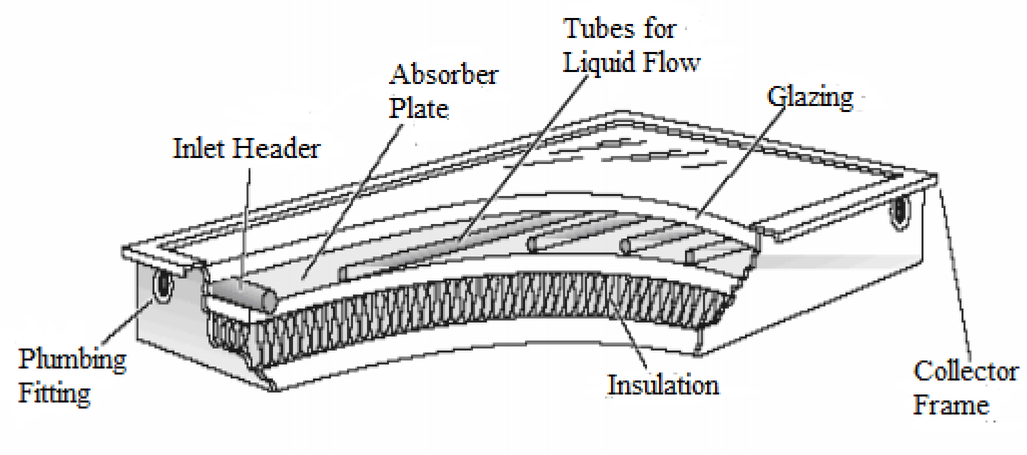


Figure 2.12: Flat plate solar thermal collector's sectional structure [23]

FPC can attain 200^{o}C temperature in empty state, so all materials being used for manufacturing the collectors must sustain so much high temperature. Solar collector absorber plate consists of flat sheet of metal having tubes spaced 10cm apart and attached to metal plate. Collector's absorber plate is covered with glass sheets to reduce heat losses through convection phenomena.

2.3.5 Evacuated Tube Collectors

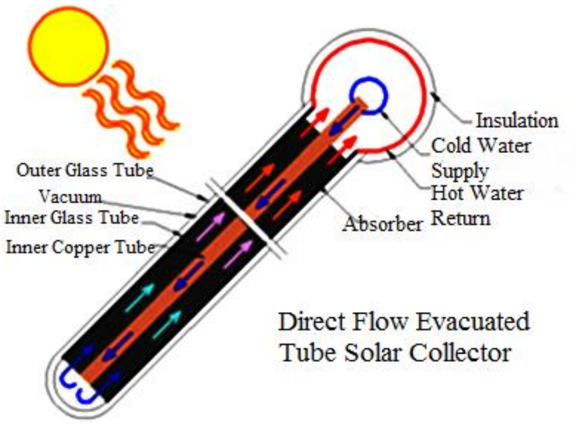
ETC (shown in Figure 2.13), typically consists of parallel arrangement of transparent evacuated glass tubes. Each tube contains an absorber tube inside, having selective coating. During manufacturing process of evacuated tubes, vacuum is created in space between two tubes by evacuating the air. So heat losses possible to occur due to convection phenomena are reduced to much extent [24].

Figure 2.13: Evacuated tube collector [24]

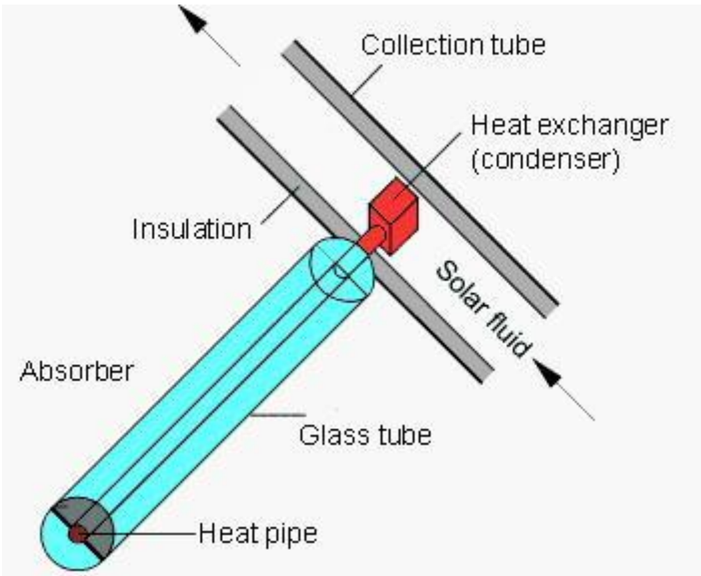
ETCs are classified into two main groups (shown in Figure 2.14) [24]:

- Direct Flow Tubes: In which heat transfer fluid flows through the absorber surface.
- Heat Pipe Tubes: A type in which heat transfer takes place between absorber and collector's heat transfer fluid.

In evacuated tube, aluminum pate is usually coated with special selective material to maximize the incident solar radiations absorption. In ETC, incident sunlight enters through outer surface of glass tube, strikes the absorber surface and then transferred into heat energy. The generated heat is transferred to the fluid flowing through collector.



(a) Direct flow evacuated tube [25]



(b) Heat pipe evacuated tube [26]

Figure 2.14: Direct flow and heat pipe evacuated tube collectors

2.3.6 Collector's Absorber Surface Coatings

Solar absorber surfaces haven been studied with spectral distribution perspective since 1950s. As radiations emitted by sun are of electromagnetic nature and display a wide range of wavelengths that can be divided into two major regions: ionizing radiations (X-rays and gamma-rays) and non-ionizing radiations (Ultra-violet radiations, visible light and infrared radiation) [6].

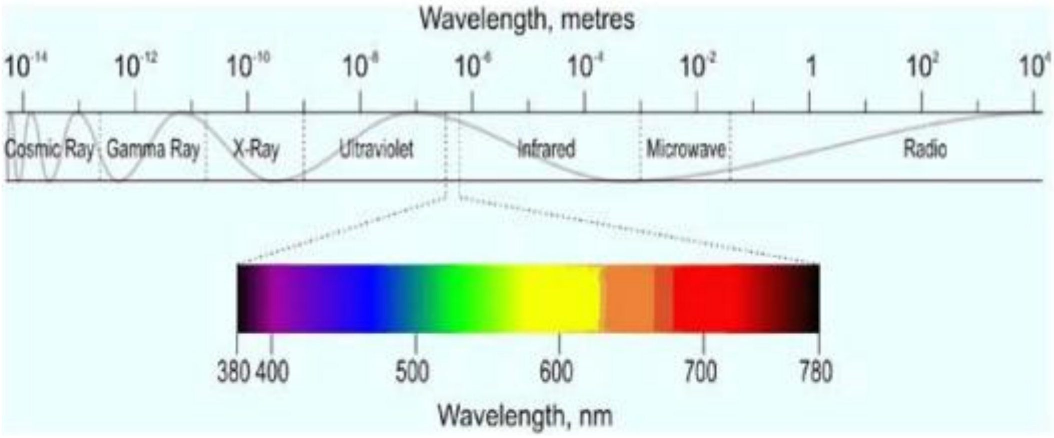


Figure 2.15: Solar radiation wavelength band [6]

Tabor [27] introduced an idea of selecting the absorber surface based on wavelength separation. A number of materials have been used in this perspective for constructing solar absorber surface. Zr-ZrO_2 [28], a high solar performance cermet coating was deposited, achieved $\alpha=0.96$ and $\varepsilon=0.05$ at $80^{o}C$. A series of metal-aluminium (M-

AlN) [28, 29] cermet materials were deposited using novel direct current magnetron sputtering technique for solar selective coatings. Many other thin film or electrolyte based materials, like black chromium/nickel [30], black cobalt, nickel pigmentation, carbon and silica [28] etc., were applied as absorber coating for achieving maximum possible absorptance and reducing emittance value. Selective absorber surface coatings being used today have much good optical properties: $90\% < \alpha < 98\%$ and $3\% < \varepsilon < 10\%$.

2.4 Optimization of Solar Water Heating System

Solar thermal collector is basic element of SWH system and tilt angle of solar collector plays very important role in performance of SWH system. Optimum tilt angle of solar collector varies from location to location and has a certain value at each location for optimizing the performance of SWH system. A lot work has been carried out regarding optimization of SWH systems based on tilt angle of solar thermal collector for different locations.

Mohd Yakup et.al., [31] developed a mathematical model and found optimum tilt angle for Brunei Darussalam considering total global solar radiations on titled surface. They concluded that tilt angle of collector should be changed 12 times in a year i.e. should be changed each month.

Adnan Shariah et.al., [32] carried out TRNSYS simulations of thermosyphon SWH installed in northern and southern Jordan for optimizing collector's tilt angle. They concluded that the optimum tilt angle for attaining maximum solar fraction equals to $\phi+(0\text{-}10^{o})$ for northern region and $\phi+(0\text{-}20^{o})$ for southern region.

R. Tang and T. Wu [33] used a simple mathematical procedure for estimating optimum tilt angle of 152 cities of China considering monthly horizontal radiations. F. Assilzadeh et.al., [34] carried out TRNSYS based simulations for finding out optimum tilt angle of ETC for tropical regions of Malaysia and concluded that collectors should be sloped at 20^{o} for attaining optimum output.

H. Khorasanizadeh et.al., [35] worked on optimization of south facing collector surfaces performance through tilt angle in Tabbas-Iran considering horizontal diffused radiations as considering parameter. They concluded that the optimum angle for warm period (Apr-Sep) equals to 10^o and for cold period (Oct-Mar) equals to 55^o.

Similarly many researchers worked on optimization of SWH system's performance through tilt angle considering different criteria like; H. Gunerhan and A. Hepbasli [36] measured tilt angel at Izmir in Turkey, H. Moghadam et.al., [37] built a MATLAB code for finding tilt angle of solar collector at Zahedan-Iran.

The literature study of solar water heating systems concludes that solar thermal technology is need of time for overcoming the prevailing energy crisis. There are many ways of utilizing solar thermal technology i.e. evacuated tube collectors, flat plate collectors and concentrated collectors. A specific way of harnessing solar radiation thermal energy depends upon output demands and location of application. Solar collector's absorber surface coating also means a lot to the performance of collector and a lot of work is carried out ad still being done on absorber surface coatings for achieving maximum absorptivity and minimum emissivity. One of the most important parameters put under consideration during installation of solar thermal collector is its tilt angle that affects its performance a lot as many scientists focused its tilt angle for optimizing the performance.

Summary

This chapter briefs about literature study of SWH systems starts from solar energy utilization, including types and designs of SWH systems. The basic component of SWH system i.e. solar thermal collector and its classification is introduced. The effect of collector's absorber surface coating is also described. The overview of SWH system optimization based on its collector's tilt angle is explained. It is concluded that:

- ETC is much more efficient than FPC as convective losses are much less because of absence of air in space between absorber and cover sheet.
- For current study, thermosyphon type passive solar water heating system is selected as it is simple in construction and recommended for domestic water heating applications. Most important one, there is no need of electric power for operating pump so such a system can also be installed in backward areas don't have electricity access.

In the next chapter, simulation model of passive SWH system is built using both ETC and FPC in TRNSYS and RETScreen software to evaluate the performance of SWH system and also to study the performance comparison of ETSWH and FPSWH systems. It is also explained that how performance of SWH system could be optimized through collector's tilt angle?

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Chapter 3

SIMULATION AND NUMERICAL MODELLING

3.1 TRNSYS: Simulation Modelling

Transient systems simulation (TRNSYS) [1] software is a quasi-steady state simulation program. TRNSYS is components based software package having flexible nature that accommodates the both researchers and practitioners regarding ever-changing needs of energy simulation community. TRNSYS software consists of two main parts [1]: engine (called kernel) and extensive library of components. Kernel reads and processes the input files, solves the system iteratively, determines convergence and thermo-physical properties, inverts the matrices, performs linear regression, interpolates external data files and plots the system variables. Regarding extensive library part, each component models the performance of one part of the system. This package enables the user to select and interconnect system's components in desired manner to build up a working system model.

3.1.1 Goal

TRNSYS software program is used for modelling of SWH system using ETC & FPC. Modelled system is hybridized with auxiliary natural gas heater as ~1.4 million tons of oil equivalent (MTOE) natural gas fuel is consumed for water heating purpose [2] in Pakistan. Overall objective of simulating this model is to evaluate the thermal performance of hybrid SWH system. Main focus of modelling this hybrid system in TRNSYS software is:

- To evaluate the thermal performance of hybrid ETSWH system and to compare with natural gas fuel based water heating system, considering useful energy produced by ETC and natural gas fuel savings achieved as indicating parameters.
- To investigate the effect of water pipeline insulation!
- To identify the differential temperature controller presence effect in terms of natural gas fuel savings possible!

- Performance of hybrid ETSWH system is also compared with hybrid FPSWH system working under same metrological and operating conditions.

3.1.2 Methodology Adopted for TRNSYS Model Simulation

A domestic scale SWH system is modelled in TRNSYS simulation program using non-concentrated solar thermal collector for the capital city (Islamabad) of Pakistan. Modelled SWH is hybridized with backup heater running on natural gas fuel to provide auxiliary heat energy required to attain desired hot water temperature and for continuing hot water supply during non-sunny time if required. The methodology used to evaluate the performance of modelled system is shown in Figure 3.1, involving all effective inputs parameters and estimated outcomes of the current study.

3.1.3 Parameters Focused for Model Simulation

The input parameters studied for analyzing the performance of modelled hybrid SWH system in TRNSYS software are listed in Table 3.1. Hybrid SWH system is modelled for a house occupied by five family members. Hot water storage tank volume equals to 75gal (~284Lit) is estimated through personal communication and market observations based on people daily hot water usage rate. Both heating elements of the storage tank are switched off as auxiliary tank heating device running on natural gas fuel is equipped in system for providing backup. Hot water draw profile estimated, for domestic usage of a five member house during winter season months, through interaction with system designers and domestic users is shown in Figure 3.2. Mass flow rate value of the system is set in accordance with hot water draw profile. Solar thermal collector area value is nominalized through optimization process for the coldest day of the year (1st Jan) according to meteonorm weather data, considering auxiliary natural gas fuel required to meet the demand as indication parameter. To maximize the solar incident radiation value, incident angle modifier setup file provided by TRNSYS database is also inserted in collector's settings. Hot water temperature monitored by differential temperature controller is set equals to 55^{o}C with upper and lower dead band (ΔT) of 5^{o}C. Differential temperature controller also protects the system from overheating and water freezing phenomenon. Water pipeline is thermally insulated with 2mm thick PVC coating to reduce the heat

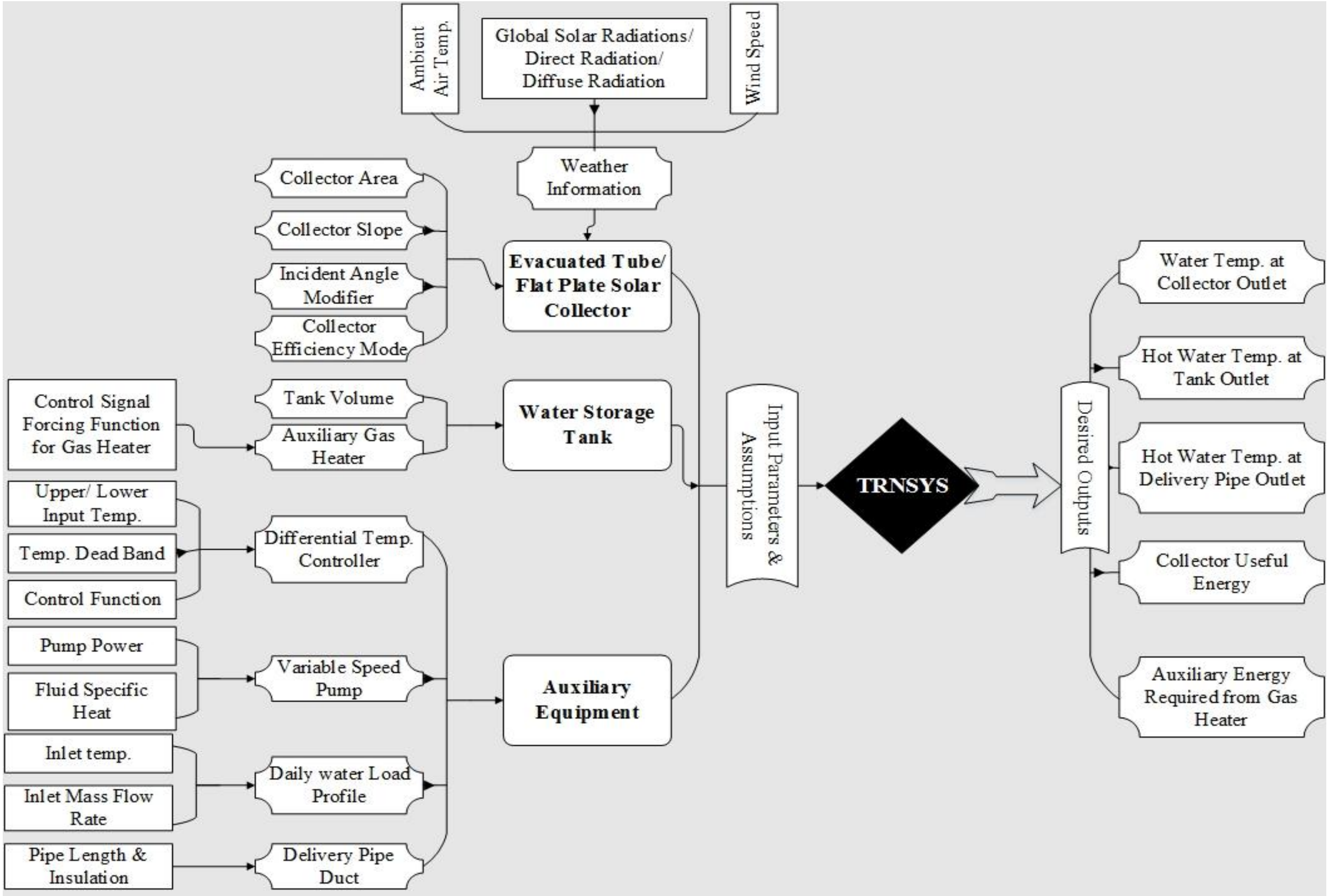

Figure 3.1: Methodology adopted to evaluate the performance of modelled hybrid SWH system in TRNSYS simulation program

losses, could occur due to temperature difference between inside flowing water and outside environment.

Table 3.1: TRNSYS simulation model input parameters

Factor	**Value**
Household Parameters	
No of Occupants	05
Operating days per week	7
Solar Thermal Collector	
Collector area	1.7 m^2
Type	ETC/ FPC
Fluid Specific heat (for Water)	4.190 kJ/kg.K
Solar tracking mode	Fixed
Storage Tank	
Storage Tank Capacity	75gal (~284Lit)
Differential Temp. Controller	
Monitoring Hot water Temp.	55^{o}C
Upper dead band	5^{o}C
Lower dead band	5^{o}C
Auxiliary Tank Heating Device (Gas Heater)	
Natural Gas Heating Capacity	53600 kJ/kg
Thermal Efficiency	0.85 Fraction

- **Assumptions Used for TRNSYS Modelling**

i) Natural gas is taken as backup fuel as it is the major fuel being used in Pakistan for water heating purpose. It is reported that ~1.4 million tons of oil equivalent (MTOE) natural gas fuel is consumed for water heating [2] because it is cheaper than liquefied oil products.

ii) Collector slope is adjusted 15^o above the latitude of location as system is designed to fulfil hot water demand in winter season [3] (October to April) specifically.

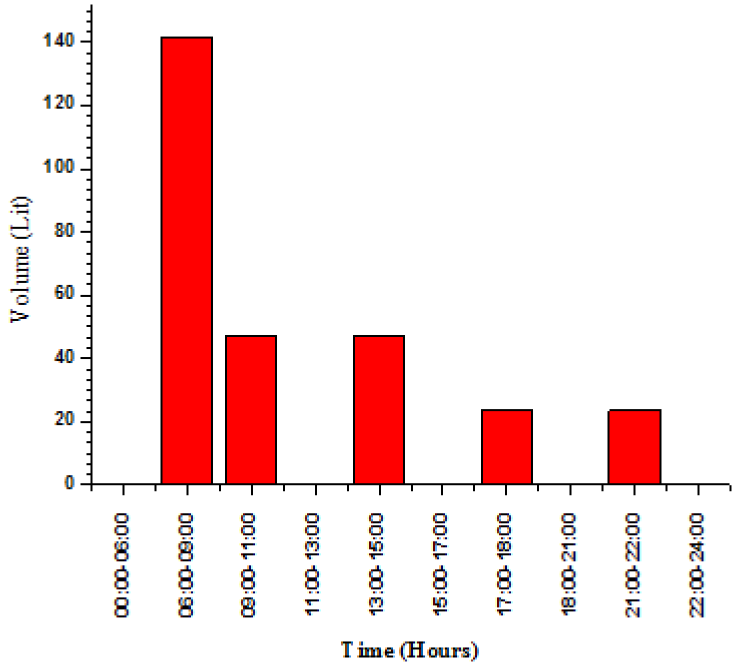

Figure 3.2: Domestic hot water draw profile

- **Weather Information of Selected Location**

Weather conditions are very important parameters for the evaluation of system's performance based on renewable energy sources specifically solar and wind.

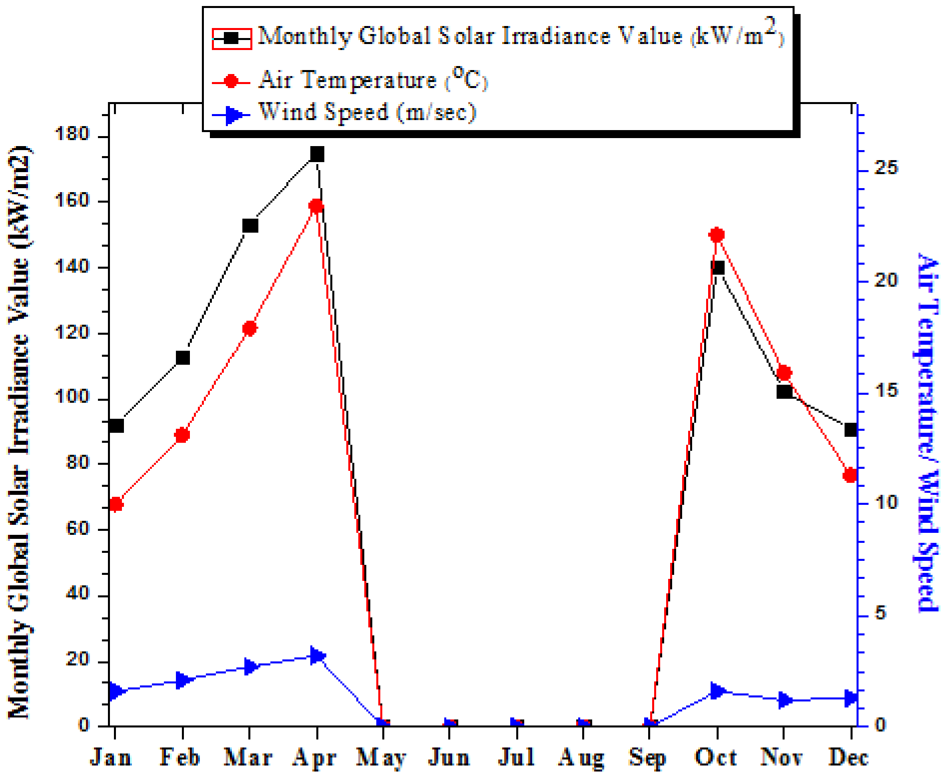

Figure 3.3: Weather information of winter season of selected location

Weather information of a location having latitude= 33.6^{o}N and longitude= 73.1^{o}E, where we are interested in evaluating the performance of hybrid SWH system in terms of useful energy produced by solar thermal collector and natural gas fuel savings, are depicted in Figure 3.3. Weather information reported by meteonorm database including global solar radiation, air temperature and wind speed are plotted for winter season (Oct-Apr) during which hot water is requirement of domestic sector.

3.1.4 Information Flow Diagram for TRNSYS Model Simulation

TRNSYS model is build up on the basis of desired system's information flow diagram. Information flow diagram of the model built for current study is shown in Figure 3.4.

Main building component of TRNSYS model is solar radiant heat energy collector which is ETC (type 71) and FPC (type 73). To hybridize the SWH system with conventional fuel for providing backup, auxiliary tank heating device (type 1226-Gas) is connected. Other additional components interconnected to build up a model are: weather information including in-plane solar radiations (global, direct and diffused radiations), wind speed, humidity and air temperature (type 99), hot water draw 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 plotter (type 65c).

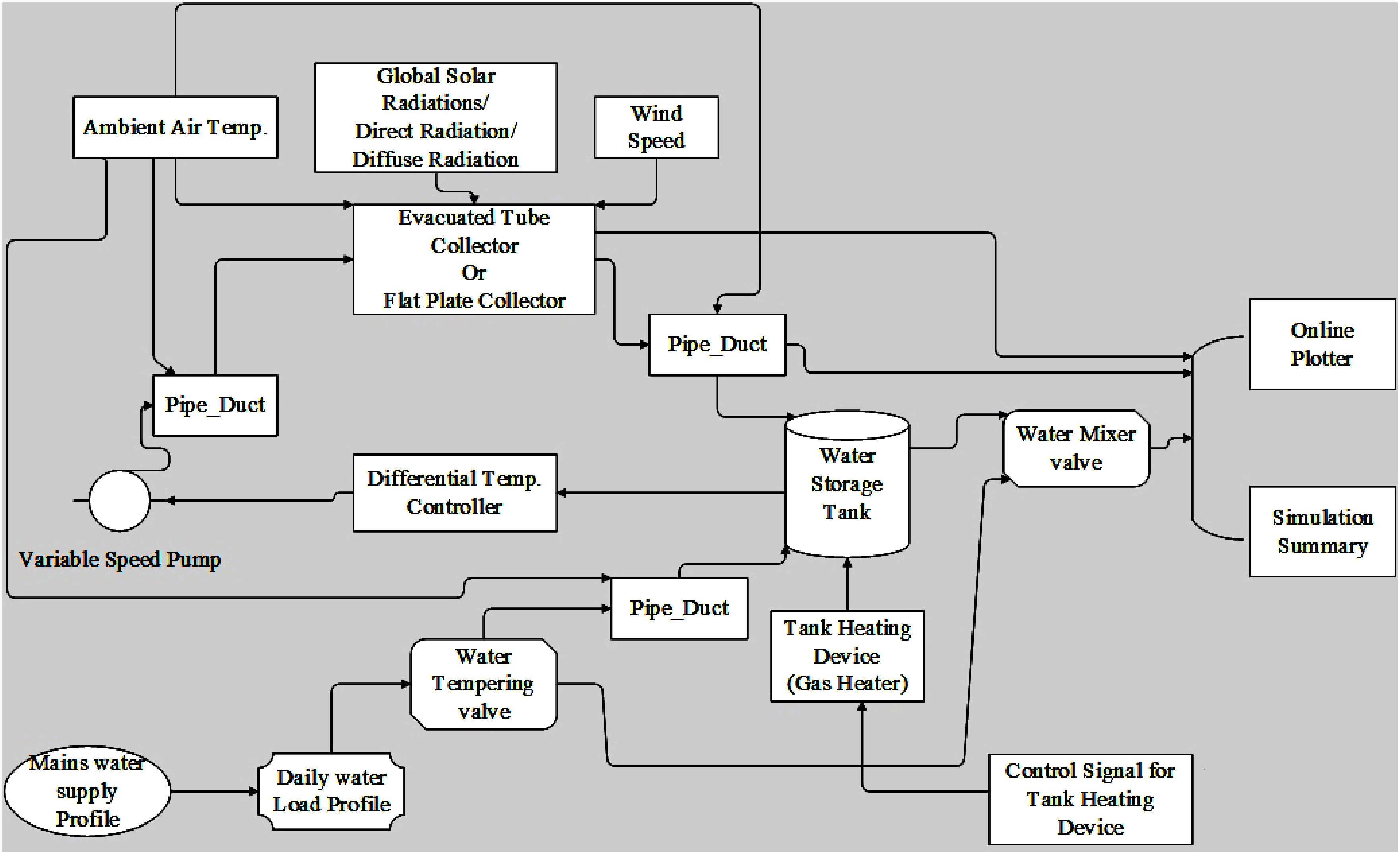

Figure 3.4: Information flow diagram for TRNSYS simulation model

3.2 RETScreen: Simulation Modelling

RETScreen is an excel based software developed by Natural Resources Canada's CANMET Energy Diversification Research Laboratory (CEDRL) using f-chart method [4]. It is used worldwide to figure out the preferential economic viability of potential renewable energy based projects at the first [5]. RETScreen software database has been made using algorithms retaining weather information reported by National Aeronautics and Space Administration, cost estimation, product information, online manuals, a website and project case studies [5]. RETScreen software can be used to evaluate the economic and environment viability of an energy project model on the basis of percentage solar fraction, NPV, IRR, payback period, BCR and GHG emissions factors preferentially [5]. The f-chart method designed on utilizability concepts could be used in predicting SWH system's performance within 1.1% of simulation outcomes for domestic SWH and 4.2% for liquid space heating [6].

3.2.1 Goal

RETScreen software simulation model is developed using ETC and FPC for Islamabad-Pakistan (latitude= 33.6^{o}N and longitude= 73.1^{o}E) for evaluating the economic viability of hybrid SWH system. RETScreen analysis is focused:

- To evaluate the comparative financial viability of hybrid ETSWH and hybrid FPSWH systems based on economic determinants: NPV, IRR, BCR and payback period.
- Environmental effect of hybrid SWH system installation is also investigated in terms of GHG emissions reductions achieved!

3.2.2 Parameters Studied for Model Simulation

The input parameters studied for analysing modelled hybrid SWH case study system in RETScreen software, are listed in Table 3.2. Hybrid SWH system is modelled for a house occupied by five members using system designing parameters and assumptions of TRNSYS simulation model.

Financial input parameters required by software to figure out the economic viability of modelled hybrid SWH system involves; average fuel cost escalation rate that is

4.10% [7] in Pakistan, average inflation rate equals to 7.75% [7], discount rate has been raised to 9.5% [8] by State Bank of Pakistan and interest rate currently exists in bank trading is 9.00% [8, 9].

Table 3.2: RETScreen energy model input parameters

Factor	**Value**
Household Parameters	
No of Occupants	06
Resource assessment	
Solar tracking mode	Fixed
Solar water Heater	
Type	ETC/FPC
Financial Parameters	
Fuel Cost Escalation Rate	4.10%
Inflation Rate	7.75%
Discount Rate	9.5%

3.2.3 Methodology Adopted for Model Simulation

A household level hybrid SWH case study system is modelled in RETScreen software. RETScreen heating project model is used for the calculation of energy production, economics based life cycle assessment and GHG emissions reduction through hybrid SWH system application in domestic sector of Pakistan. The methodology used to study the economic and environmental behaviour of modelled hybrid SWH system for capital city (Islamabad) of Pakistan is shown in Figure 3.5; involving all inputs parameters and estimated outcomes of current study.

3.2.4 How RETScreen and TRNSYS Models are Inter-linked

In this work, TRNSYS software is used to evaluate the thermal performance of hybrid SWH system while RETScreen simulation model is used for economic and environmental study of TRNSYS modelled hybrid SWH system. These two simulation programs are interlinked in such a way that hybrid SWH system is modelled in both simulation programs using same system designing parameters that are interpreted in Figure 3.6.

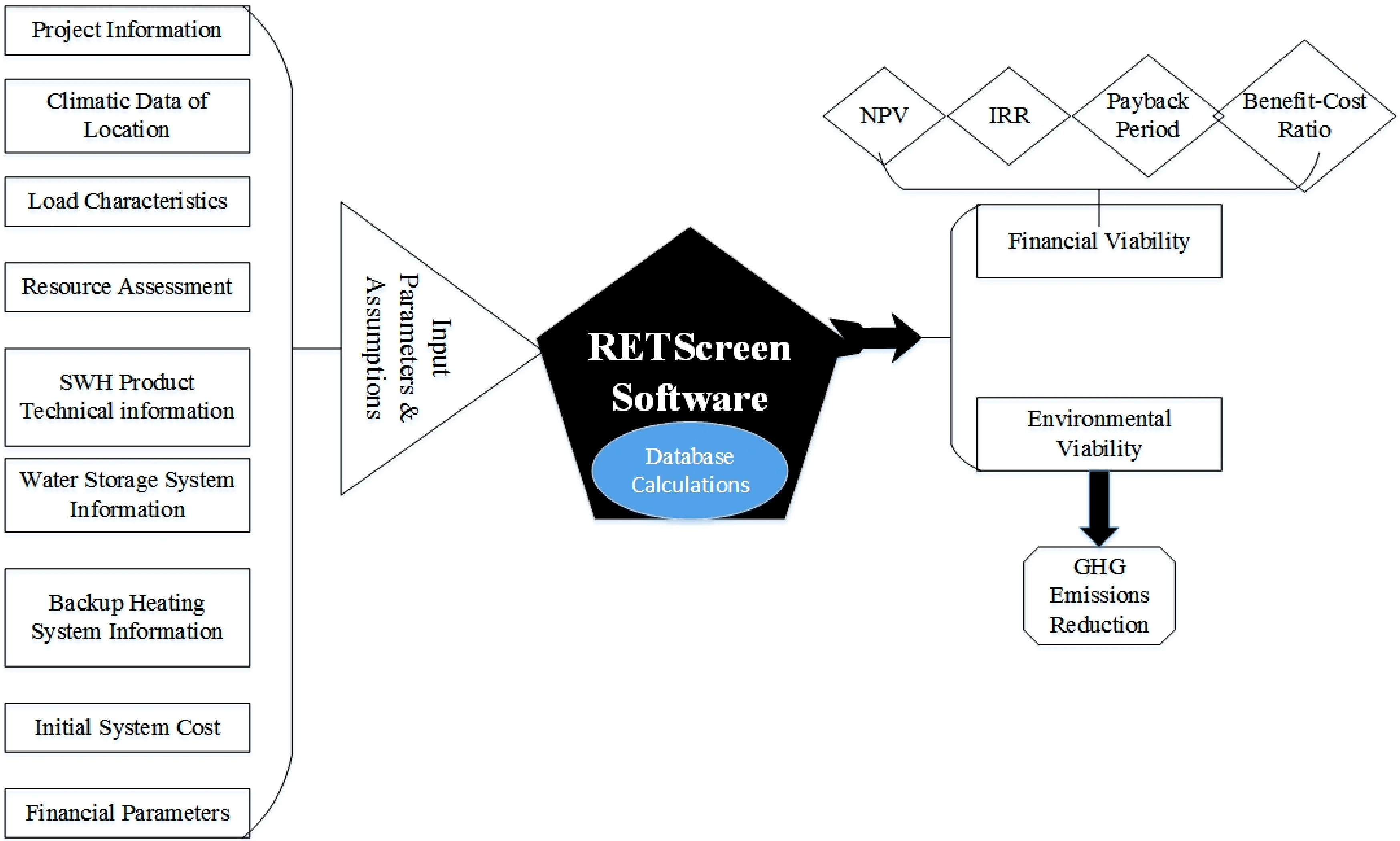

Figure 3.5: Methodology adopted to evaluate the economic and environmental viability of modelled hybrid SWH system through RETScreen simulation program

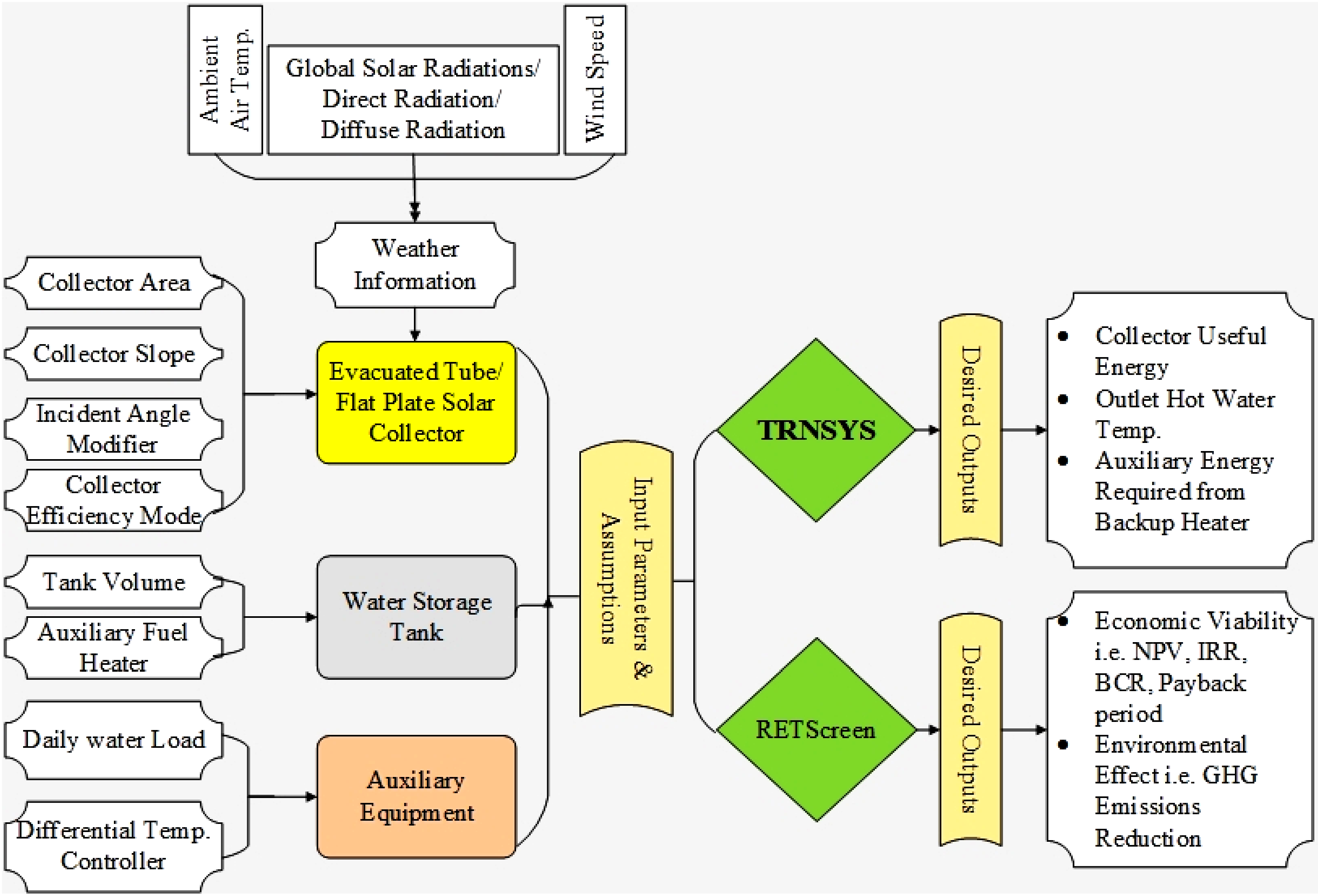

Figure 3.6: How RETScreen and TRNSYS simulation models are inter-linked

3.3 Numerical Modelling

Numerical model of non-concentrated solar thermal collector is developed using m-file user interface of MATLAB program [10]. MATLAB is one of the most widely used tools for high performance numerical computation and visualization. It has hundreds of functions for graphics, technical computation and animation built in its database.

3.3.1 Goal

The aim of developing numerical model of solar thermal collector using mathematical relations is to find out the optimum tilt angle of solar thermal collector at which collector will give the best performance considering useful energy of collector as deciding parameter.

3.3.2 Solar Collector's Numerical Model

Numerical model of non-concentrated solar thermal collector start from solar constant to collector's efficiency and fluid outlet temperature consists of six major characteristic parameters:

i. Available solar radiations on sloped surface
ii. Absorbed solar radiations
iii. Solar collector's energy balance
iv. Collector overall heat loss coefficient
v. Efficiency of solar collector
vi. Fluid outlet temperature

Mathematical relations being used to calculate characteristic processes of solar collector (shown in Figure 3.7) and to develop the m-file numerical model are describe here!

- **Available Solar Radiations on sloped Surface**

Available solar radiations on sloped surface can be calculated using isotropic sky model proposed by Hottel and Woertz [6, 12]. According to this model, combination of diffused and ground reflected radiations is isotropic while total radiations on a sloped surface equals to sum of beam radiations, diffuse radiations and ground reflected components of incident radiations [4,5].

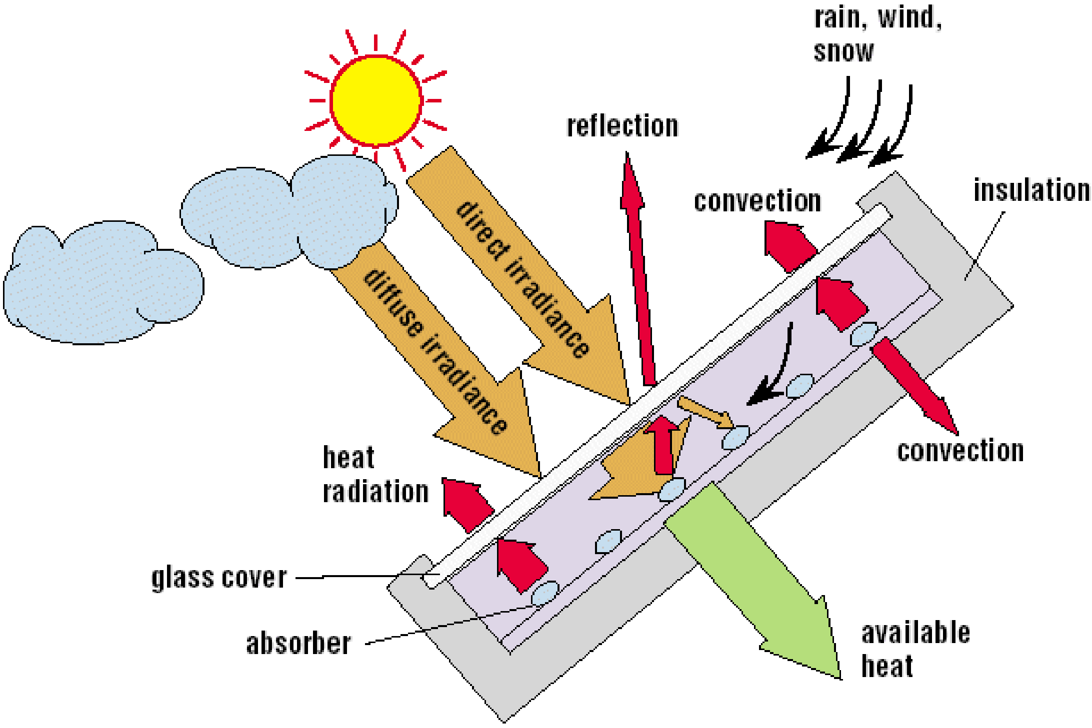

Figure 3.7: Characteristic processes of solar thermal collector [11]

Total solar radiations available on sloped surface (I_T) are calculated by [6]:

$$I_T = I_b R_b + I_d (\frac{1+cos\beta}{2}) + I\varsigma_g (\frac{1-cos\beta}{2}) \tag{3.1}$$

In equation 3.1; R_b factor, Ratio of beam radiations on titled surface to that on horizontal surface, developed for hourly periods is given as [6]:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{3.2}$$

For northern hemisphere:

$$\cos\theta = \cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta \tag{3.3}$$

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{3.4}$$

Beam and diffused components of hourly incident solar radiations are calculated using hourly clearness index (k_T) equals to ratio of hourly incident radiation on horizontal surface to that of hourly extraterrestrial radiations [6].

- **Absorbed Solar Radiations**

Performance of solar collector can be predicted on the basis of absorbed solar radiant energy of collector's absorber surface. Incident solar radiations have three different spatial distributions: beam radiation components, diffuse radiation components and ground reflected radiation components, and each part is treated separately [6]. Using isotropic model concepts for hourly periods, absorbed solar radiations (S) can be calculated by modifying equation 3.1 as [6]:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+cos\beta}{2}\right) + I\varsigma_g (\tau\alpha)_g \left(\frac{1-cos\beta}{2}\right) = (\tau\alpha)_{av}.I_T \qquad (3.5)$$

Transmittance absorptance product ($\tau\alpha$) can be found with the help of incidence angle and using following relations [6]:

For beam radiation component: $(\tau\alpha)_b = 1.01 * \tau_b * \alpha_b$ (3.6)

For diffuse radiation component: $(\tau\alpha)_d = 1.01 * \tau_d * \alpha_d$ (3.7)

For ground-reflected radiation component: $(\tau\alpha)_g = 1.01 * \tau_g * \alpha_g$ (3.8)

And: $(\tau\alpha)_{av} = o.96 * (\tau\alpha)_b$ (3.9)

- **Solar Collector's Energy Balance**

Energy balance of solar collector indicates the conversion of absorbed solar radiations into three forms: useful energy gain of collector (Q_u), thermal and optical losses. Thermal losses of the collector occur through conduction, convention and infrared radiation from surroundings of the collector. In steady state, useful energy gain of solar collector is defined by following relation [6]:

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] = A_c F_R [S - U_L(T_{fi} - T_a)] \qquad (3.10)$$

Here: $U_L(T_{pm} - T_a)$ = Thermal losses of the collector

- **Collector Overall Heat Loss Coefficient**

Collector overall heat loss coefficient (U_L) is combination of three heat loss coefficients: collector's top loss coefficient (U_t), collector's back loss coefficient (U_b) and collector's edge loss coefficient (U_e) [6], are calculated using following relations:

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}}\left[\frac{T_{pm}-T_a}{(N+f)}\right]^e} + \frac{1}{h_w}\right)^{-1} + \left[\frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{\frac{1}{\varepsilon_p+0.00591Nh_w} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N}\right] \quad (3.11)$$

$$U_b = \frac{k}{L_b} \quad (3.12)$$

$$U_e = \frac{(UA)_{edge}}{A_c} = \frac{(k/L_e)*A_{edge}}{A_c} \quad (3.13)$$

In equation 3.11:

$$f = (1+0.089h_w - 0.1166h_w\varepsilon_p)(1+0.07866N) \quad (3.14)$$

$$C = 520(1-0.000051\beta^2) \quad (3.15)$$

$$e = 0.430(1-100/T_{pm}) \quad (3.16)$$

- **Efficiency of Solar Collector**

Collector's efficiency is measure of collector performance; equals to ratio of useful energy gain and incident solar radiations [6]:

$$\eta = \frac{Q_u}{I_T A_c} = \frac{q_u}{I_T} = F_R(\tau.\alpha) - (F_R U_L)\frac{T_{fi}-T_a}{I} \quad (3.17)$$

- **Fluid Outlet Temperature**

Collector's performance is affected by overall loss coefficient and internal fluid heat transfer. Both U_L and h_{fi} are functions of temperature to much extent. Mean temperature of fluid circulating in collector can be calculated using following relation [6];

$$T_{fm} = T_{fi} + \frac{Q_u / A_c}{F_R U_L}(1 - F'') \qquad (3.18)$$

And temperature of fluid at collector exit at particular instant can be calculated using the following relation [6]:

$$T_{fo} = T_{fi} + \frac{I\eta A_c}{(m^{\cdot} C_p)} = T_{fi} + \frac{A_c F_R [S - U_L (T_{fi} - T_a)]}{(m^{\cdot} C_p)} \qquad (3.19)$$

Summary

This chapter explains the parameters and methodologies used for modelling of hybrid SWH system to study the thermal and economic behavior of modelled system through TRNSYS and RETScreen simulation programs respectively. It is also described that how TRNSYS and RETScreen simulation programs are inter-linked. Complete set of mathematical relations, used for numerical modelling of solar collector in MATLAB m-file user interface for finding put optimum tilt angle, is described. The next chapter explains about development of hybrid SWH system set-up that is modelled in TRNSYS/ RETScreen using ETC. Also tells about the conditions under which experimentation is carried out and how?

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Chapter 4

EXPERIMENTATION

4.1 Experimental Set-up

Experimental model developed for current study mainly consists of:

- Evacuated Tube Solar Thermal Collector
- Storage Tank
- Multi-fuel Furnace

In modelled system, 20 tubes heat pipe evacuated tube solar thermal manipulate is attached with water storage tank of capacity 50gal (~190Lit). A multi-fuel furnace having two combustion chambers is designed and fabricated with heating section of storage tank at its base.

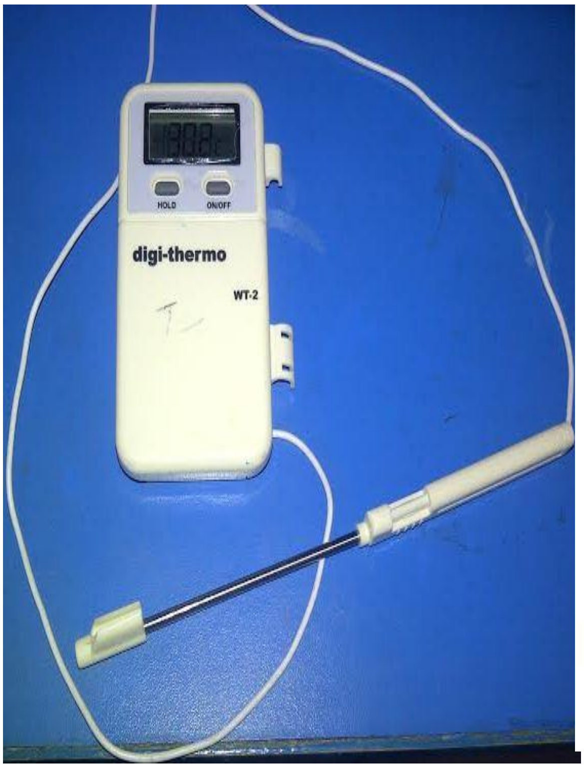
4.2 Experimentation Tools

Tools used for building experimental set-up and measuring experimental values are: wilo pump, thermocouple and light meter (shown in Figure 4.1). Among these, wilo pump is special type of pump designed for hot water circulation through solar thermal collector. Specifications of variable speed wilo pump used in experimental set-up are tabulated in Table 4.1. Thermocouple is a temperature sensor used for measuring hot water temperature. Light meter has a light sensor attached with digital display unit shows the measured global solar irradiance value in three different measuring units: Fahrenheit, Kelvin and W/m^2 (S).

Table 4.1: Specifications of wilo pump

Parameter	**Value**
Variable Speed Power	46, 67, 93 W
Voltage	220V/50Hz
Current	0.40-1 A
Flow rate (Q)	13 Lit/min
Head	5 m

(a) Wilo pump



(b) Thermocouple

(c) Light meter

Figure 4.1: Experimental Tools

4.3 Solar Water Heating System

SWH system in from of heat pipe evacuated tube solar thermal manipulate (shown in Figure 4.2), comprised of parallel arrangement of twenty heat pipe type evacuated tubes.

Each evacuated tube is made up of two layers of borosilicate glass (a type of glass having very low iron content). A special absorbing film is placed between two glass tubes that enables the evacuated tube to absorb 90-92% of solar incident ultraviolet rays. During manufacturing process, air is evacuated from inside the tube to avoid the heat losses possible to occur due to convection phenomena, that's why called as evacuated tube. Working theory of evacuated tube in elaborated in Figure 4.3.

Figure 4.2: Heat pipe evacuated tube solar thermal manipulate

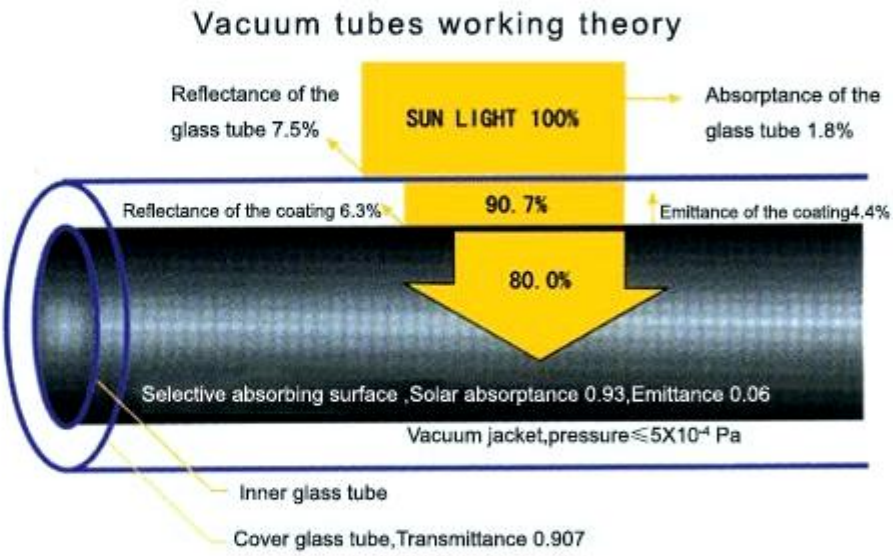


Figure 4.3: Working theory of evacuated tube [1]

4.4 Hybridization of SWH System with Conventional Fuel

SWH system i.e. heat pipe evacuated tube solar thermal manipulate is hybridized with conventional fuel using multi-fuel furnace, mainly to provide backup for fulfilling hot water requirement during non-sunny and cloudy hours. Solar thermal manipulate is connected with multi-fuel furnace using pressure pipe having cotton wool and foam insulation to reduce heat losses during hot water flow. Evacuated tube solar thermal manipulate hybridized with conventional fuel, system is shown in Figure 4.4.

Multi-fuel furnace is used to hybridize the SWH system with conventional fuel. The designing and fabrication of multi-fuel furnace is described here!

Figure 4.4: Heat pipe evacuated tube solar thermal manipulate connected with multi-fuel furnace

4.4.1 Multi-fuel Furnace Design

Multi-fuel furnace designed has two combustion chambers: one for natural gas fuel combustion and other for wood biomass combustion where coal can also be burnt. During designing phase, biomass combustion chamber is designed below the natural gas combustor of gas geyser and water drum of geyser is used as hot water storage tank. CAD model of complete design involving storage tank and combustion chambers is shown in Figure 4.5.

4.4.2 Furnace Fabrication

Furnace model (shown in Figure 4.5) fabrication process involves: materials selection for furnace chasing, insulation material and manufacturing operations performed for modifying the selected material into a furnace shape.

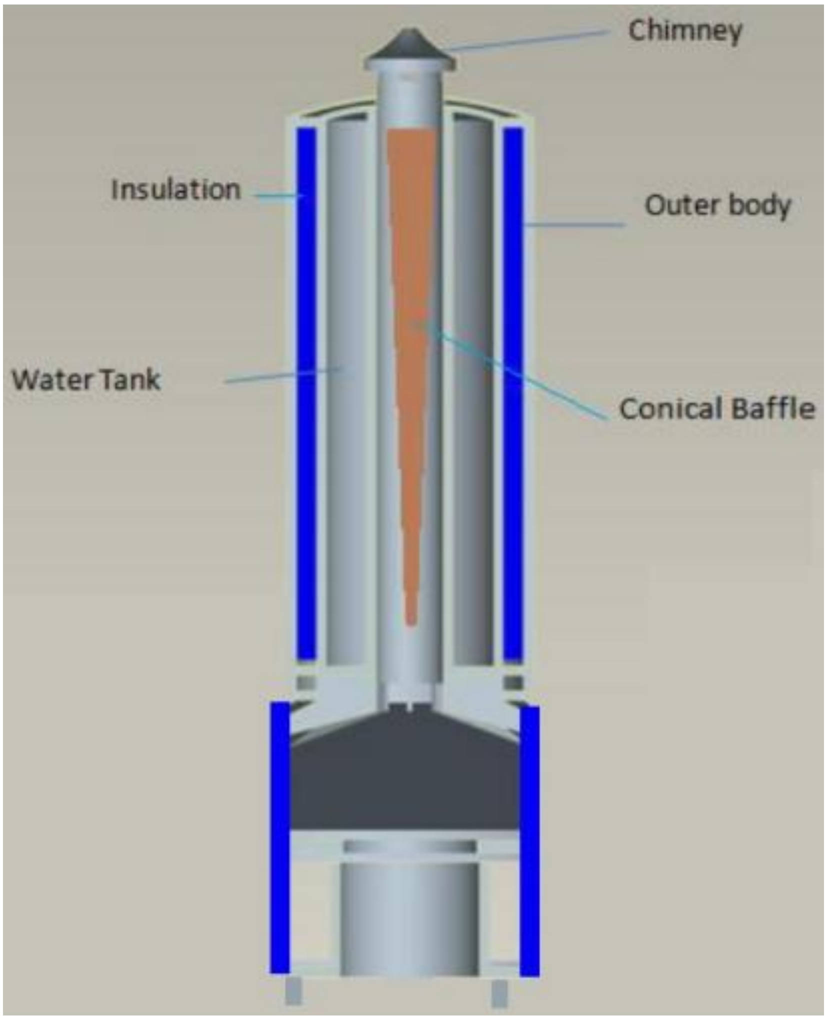


Figure 4.5: CAD model of backup system incorporating hot water storage tank

- **Furnace Materials**

For furnace wall; corrugated galvanized iron (CGI) building material is used. CGI is composed of hot-dip galvanized mild steel sheets that are passed through cold rolling process to produce corrugated pattern in their shape. These sheets are manufactured with varying thickness measured in Birmingham Wire Gauge (BWG). For outer wall of furnace BWG-20 sheet is used while BWG-18 is used for inner wall of furnace. Mild steel (MS) plate is used to manufacture the supporting feet of furnace and also of water storage tank to rest the tank above the furnace. Mild steel material is also used for making the angle iron and supports of ventilation sliding system. Stainless steel pipes of 18 gauges with square cross section are used for manufacturing furnace frame.

For providing insulation between inner and outer wall of furnace, glass wool insulation is used. This insolation material is thin and light in weight. The superiority of this insolation material over others is; it is also moisture proof material along with reliable thermal insulator.

- **Furnace Manufacturing Process**

During manufacturing process, cutting operation is performed on metal sheets and stainless steel pipes to resize them according to design requirements. Edges of the sheets are filled to make them smooth. Holes are drilled using high power drilling machine at required places. Aluminum sliding mechanism is attached on angle iron using riveting operation. All the metal sheet pieces are joined together using electric arc welding operation. All other joining operations either of angle arc welding on outer surface of wall or water tank welding on supports are also performed through electric arc welding. After completing the manufacturing operations, hand grinder and sanding operations are performed for finishing and cleaning the surface respectively. Complete manufacturing process of furnace starting from metal sheets cutting to last step of painting is illustrated in Figure 4.7 and parts of the furnace being fabricated as result of this process are shown in Figure 4.6.

(a) Fuel charging door (upper) and furnace cleaning door (lower)

(b) Furnace ventilation way

Figure 4.6: Furnace fabricated parts

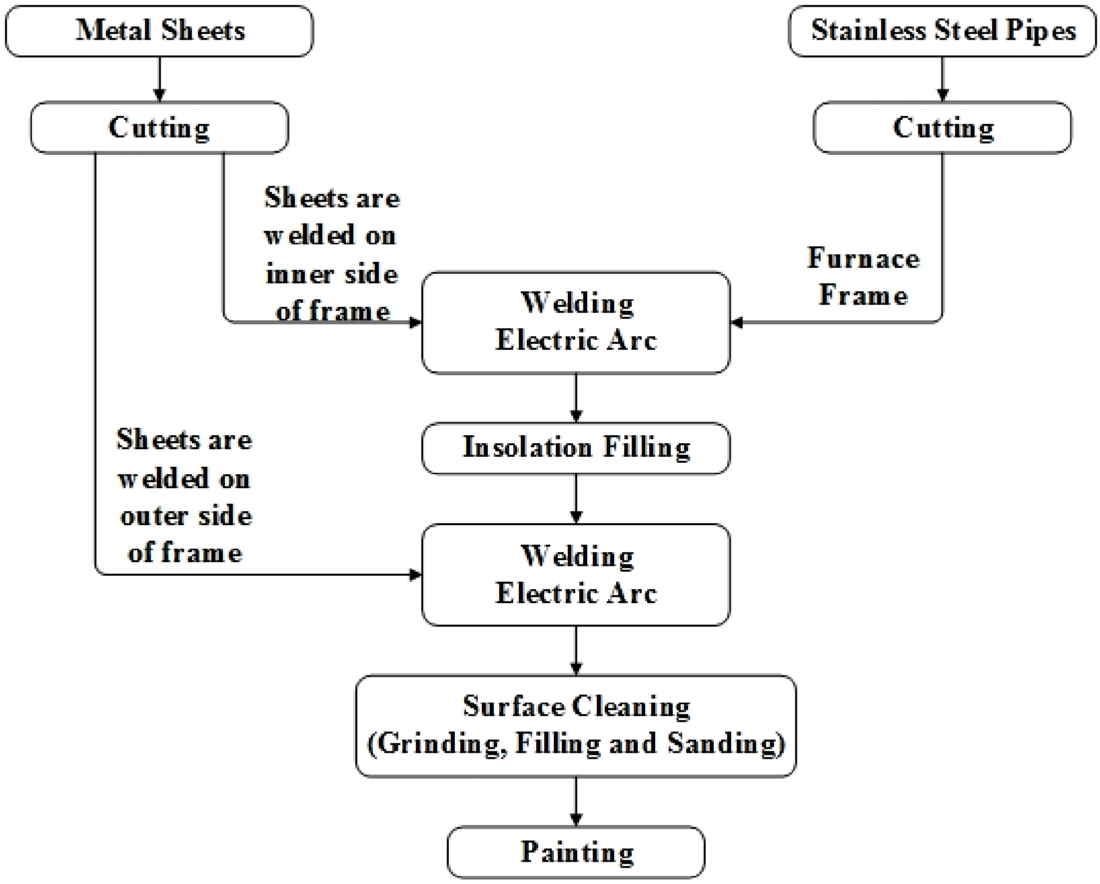


Figure 4.7: Furnace manufacturing process flow chart

- **Final Design**

The specifications of furnace final design (shown in Figure 4.8) manufactured using manufacturing process mentioned Figure 4.7 are tabulated in Table 4.2.

Table 4.2: Specifications of furnace final design

Parameter	**Specifications**
Water tank capacity	50gal (~190Lit)
Furnace fuel charging door size	1ft x 0.5ft (300mm x 150mm)
Air vent size	0.67ft x 0.5ft (200mm x 150mm)
Furnace biomass chamber fuel capacity	5kg (approx.)
Ash removal tray	1ft x 1ft (300mm x 300mm)

Figure 4.8: Furnace final Design: involving fuel combustion chambers and hot water storage tank coupled

4.4.3 Furnace Automation

Furnace combustion operation is automated by controlling the opening and closing of air supply system (as shown in Figure 4.9) through microcontroller-Arduino UNO.

Figure 4.9: Air ventilation sliding mechanism

Hot water temperature is sensed at storage tank outlet using thermocouple. Furnace automation function is programmed in such a way that as hot water temperature reaches to 60^{o}C, controller shuts down the air vent by actuating the motor in anti-clockwise direction and combustion process is stopped as air supply is being stopped. In lower range, as hot water temperature reaches to 50^{o}C, controller actuates the motor in clockwise direction causes the air vent to open again and combustion process starts

4.4.4 Furnace Fuel Calculations

Fuel required to be burnt for attaining certain temperature is function of ΔT. Higher the value the ΔT, larger the value of fuel would be required for attaining desired temperature. The fuel required to be burnt for attaining certain ΔT value can be calculated as[2];

$$q = m * C_p * \Delta T \tag{4.1}$$

$C_p = 4.2 kJ / kg.^{o}C$

m = mass of fluid

Fuel required is directly proportional to heat energy (q) value that is characteristic parameter of each fuel, as:

- Combustion of 1 kg natural gas produces ~53,600 kJ/kg heat energy
- While 1 kg dry wood produces ~16,300 kJ/kg heat energy (on complete combustion)
- Combustion of 1 kg coal on complete combustion produces ~30,700 kJ/kg

4.5 Experimentation Procedure

After completing the development of experimental set-up, experimentation is performed for August, 2014 days. During experimentation, main focus was on collector’s outlet hot water temperature against 22kg/h mass flow rate value and solar incident radiations available during day time. Fuel required to fulfill the hot water demand during non-sunny time is also calculated. Hourly global solar irradiance values available during the days for which experimentation is carried out are shown in Table 4.3.

Table 4.3: Hourly global solar irradiance value for the days during which experimentation is carried out

Time (Hour)	**Hourly Global Solar Irradiance value** (W/m^2)	
	Aug 17, 2014	Aug 18, 2014
7:00	110	113
8:00	232	357
9:00	401	583
10:00	553	721
11:00	784	770
12:00	933	882
13:00	927	804
14:00	823	719
15:00	683	697
16:00	577	531
17:00	344	392
18:00	248	201
19:00	50	27

Summary

Development of experimental SWH system set-up is described and each set-up component is explained. Hybridization of SWH system with conventional fuel is elaborated though furnace designing, fabrication, automation and fuel calculation method. The experimentation procedure is also explained. It is concluded that natural gas fuel is better than wood biomass for using as back-up fuel because of having higher heating value. It is also observed that mass flow rate of flowing fluid affects the collector's outlet hot water temperature a lot, as mass flow rate corresponds to the resident time of flowing fluid inside the collector that directly relates to the amount of absorbed useful energy causing increase in flowing fluid temperature. In following chapter, all simulation and experimentation outcomes and observations are illustrated and discussed!

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Chapter 5

RESULTS AND DISCUSSIONS

5.1 TRNSYS Simulation Outcomes

TRNSYS outcomes are analyzed on the basis of solar collector's useful energy produced and natural gas fuel savings as result of replacing gas water heater with hybrid ETSWH system, presence of differential temperature controller and water pipeline insulation. Comparison of hybrid ETSWH and hybrid FPSWH systems is also analyzed and discussed.

5.1.1 Evacuated Tube Collector's Useful Energy

Monthly useful energy produced by ETC is plotted against available monthly solar radiations in Figure 5.1.

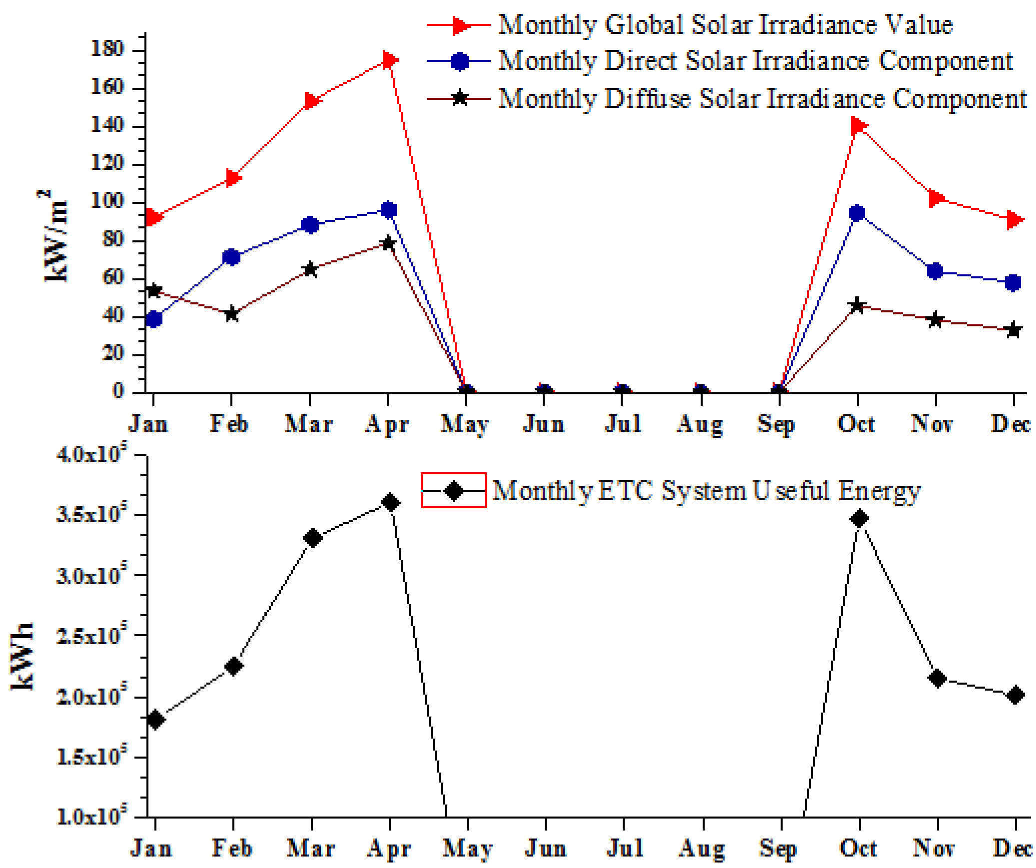

Figure 5.1: Monthly useful energy produced by ETC

It is observed that increase in global solar irradiance value results in increased ETC useful energy value. Analysis of Figure 5.1 shows that this trend is not followed for month of Jan. In this month, global solar irradiance value increases compared to last month but ETC useful energy produced value decreases. The reason is the global solar radiations mainly consist of two components; direct radiation component and diffused radiation component. Among these; direct component has more effective solar thermal energy intensity as compared to diffused component that's why higher the value of direct component would result in greater value of useful energy produced by solar collector. As analysis shows that on moving from Dec to Jan, monthly global solar irradiance value increases by 1.42% but there is 10.02% decrease in ETC useful energy produced value. The reason of this effect is; decrease in direct component of global solar radiations by 33.4% rather than being increased with increase in global solar irradiance value. While for remaining months, increase in global solar irradiance value accompanies the increase in direct radiation component that consequently results in higher useful energy produced value with respect to last month and vice versa

5.1.2 Hybrid ETSWH System's Performance

Results plotted in Figure 5.2 and Figure 5.3 illustrate that how much natural gas fuel could be possibly saved by replacing gas water heater with hybrid ETSWH system. Natural gas is one of the major conventional fuels being consumed for water heating purpose during winter season in Pakistan. That's why we come across severe natural gas shortage issue instead of having one of the world's largest natural gas reserves called as "Sui". Hybrid ETSWH system consists of ETC and gas heater to provide backup for non-sunny time. Analysis of Figure 5.2 and Figure 5.3 shows that monthly natural gas fuel savings possible are: 23.58% (for Jan), 31.15% (for Feb), 35.41% (for Mar), 41.49% (for Apr), 41.47% (for Oct), 30.37% (for Nov) and 25.98% (for Dec). Results elaborate that natural gas fuel savings achieved for Apr month has highest value while for Jan month has lowest value. The reason is; higher the value of useful energy produced by ETC, greater would be the natural gas fuel savings (affirmed by analysis of Figure 5.1 and Figure 5.2). Natural gas fuel savings are also linked with air temperature; lower the value of air temperature leads to smaller solar irradiance value (i.e. lower solar thermal collector's useful energy produced value), so greater would be the value of natural gas fuel required to fulfill hot water demand and consequently less natural gas fuel savings would be possible.

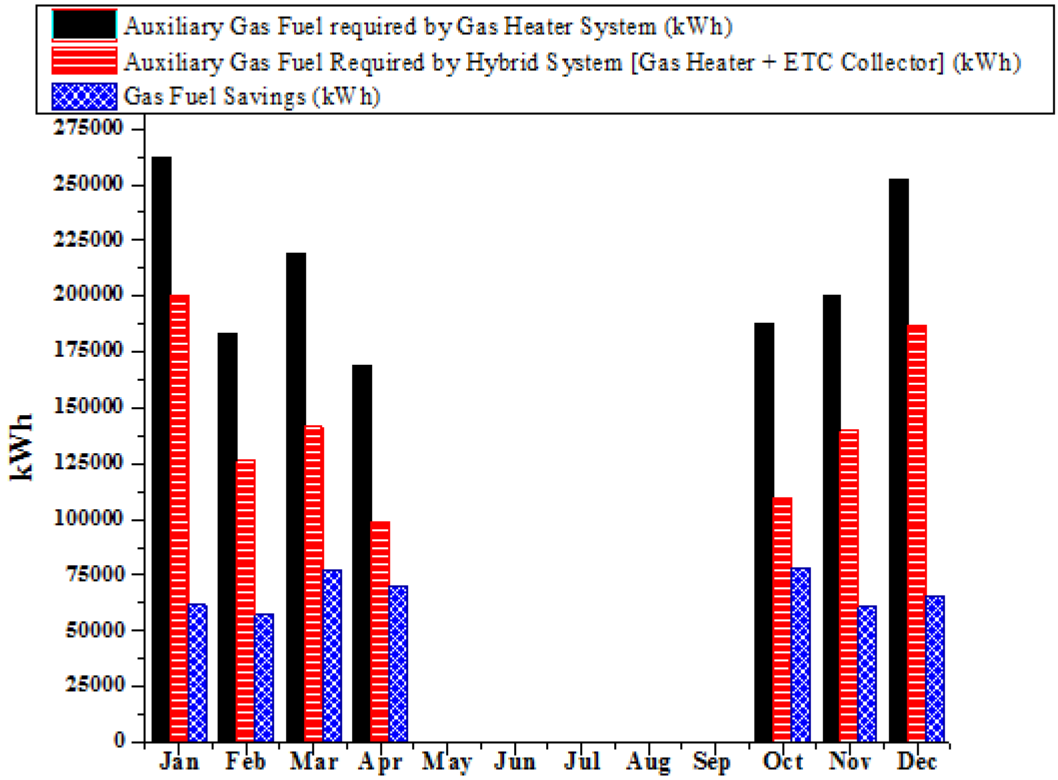

Figure 5.2: Hybrid ETSWH system's performance in terms of kWh-gas fuel savings

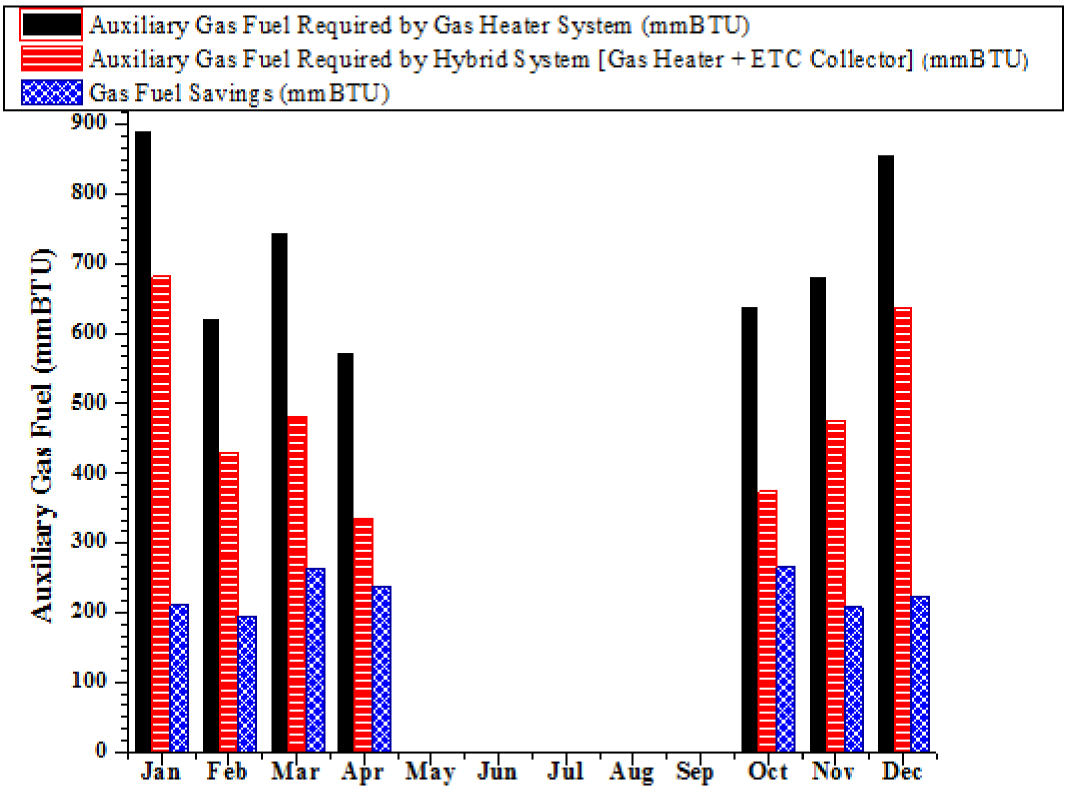

Figure 5.3: Hybrid ETSWH system's performance in mmBTU-gas fuel savings

5.1.3 Differential Temperature Controller Presence Effect on Hybrid ETSWH System's Performance

Differential temperature controller increases the operating efficiency of a heating system. It controls the water circulation system based on temperature difference between storage tank and solar thermal collector. It also monitors the temperature of water delivered at user end keeping in view the set point temperature along with upper and lower dead bands. Results plotted in Figure 5.4 and Figure 5.5 elaborate how much natural gas fuel savings are possible through insertion of differential temperature controller in hybrid ETSWH system because this controller that provides protection against overheating and freezing to pipe.

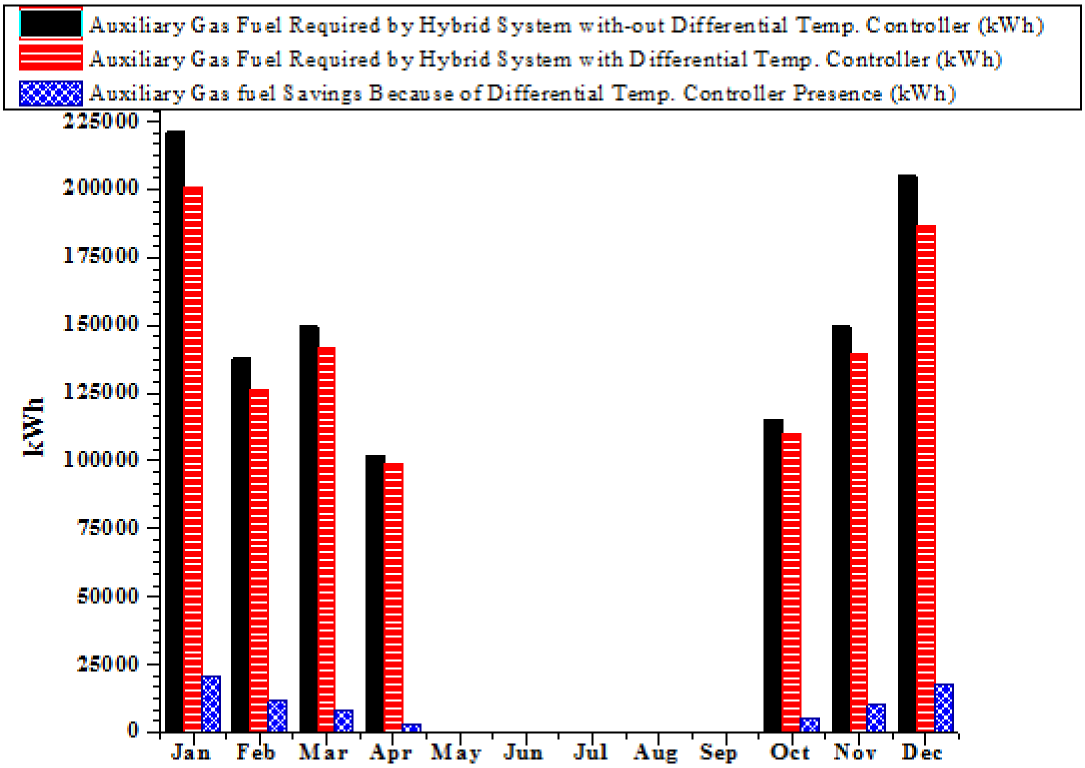

Figure 5.4: Differential temperature controller presence effect on hybrid ETSWH system's performance in kWh-natural gas fuel savings

Analysis of the Figure 5.4 and Figure 5.5 interpret that 9.32% (for Jan), 8.38% (for Feb), 5.39% (for Mar), 3.16% (for Apr), 4.58% (for Oct), 6.63% (for Nov) and 8.77% (for Dec) monthly natural gas fuel savings are possible due to differential temperature controller presence. Percentage effect of controller presence effect is smaller for a month in which less value of natural gas fuel is required and vice versa. The reason behind this observed effect is available value of useful energy; higher the value of useful energy available, less natural gas fuel amount would be required and consequently smaller would the effect of differential temperature controller presence in terms of natural gas fuel savings achieved.

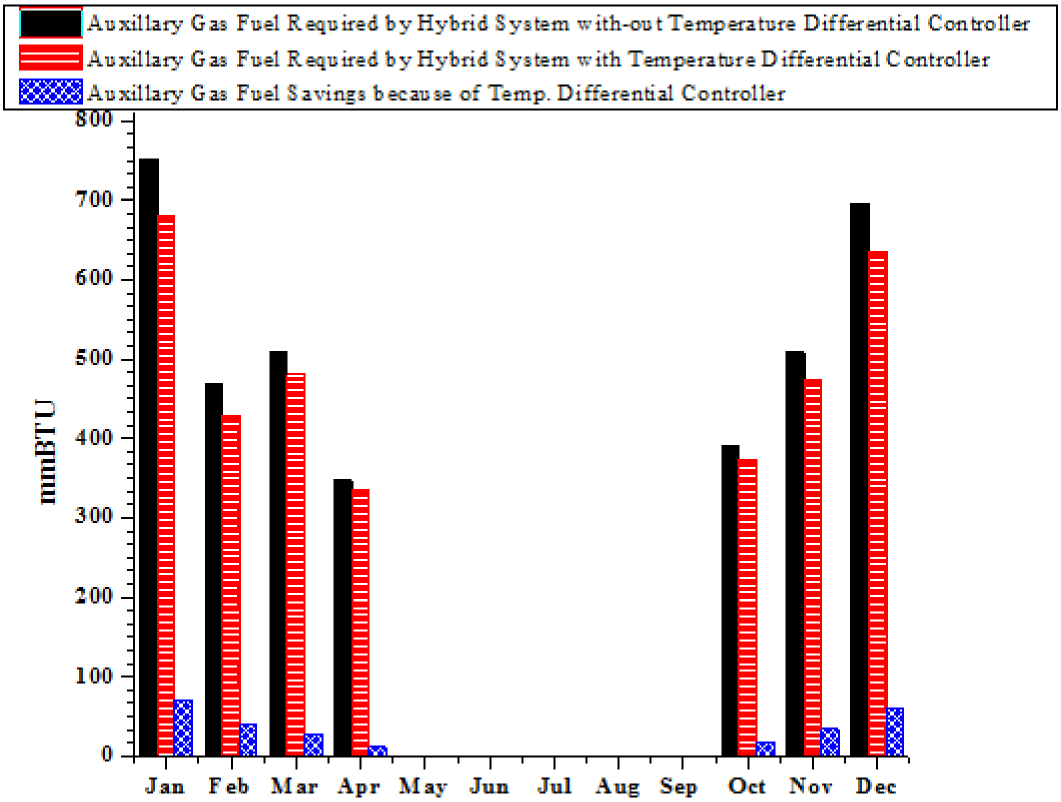

Figure 5.5: Differential temperature controller presence effect on hybrid ETSWH system's performance in mmBTU-natural gas fuel savings

5.1.4 Water Pipeline Insulation Effect 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 pipeline, heat transfer takes place between inside flowing hot water and outside ambient through conduction phenomena because of temperature difference. To reduce the heat losses due to conduction through pipeline wall, a 2mm polyvinyl chloride (PVC) insulation coating is used resulted in 42.56% [1] reduction in heat loss co-efficient for a location having average wing speed equals to 2.4m/sec. Effect of water pipeline insulation in terms of reduction in natural gas fuel requirement to achieve the desired hot water temperature is: 43.66% (for Jan), 43.47% (for Feb), 42.97% (for Mar), 41.82% (for Apr), 42.03% (for Oct), 42.80% (for Nov) and 42.86% (for Dec) as plotted in Figure 5.6 and Figure 5.7.

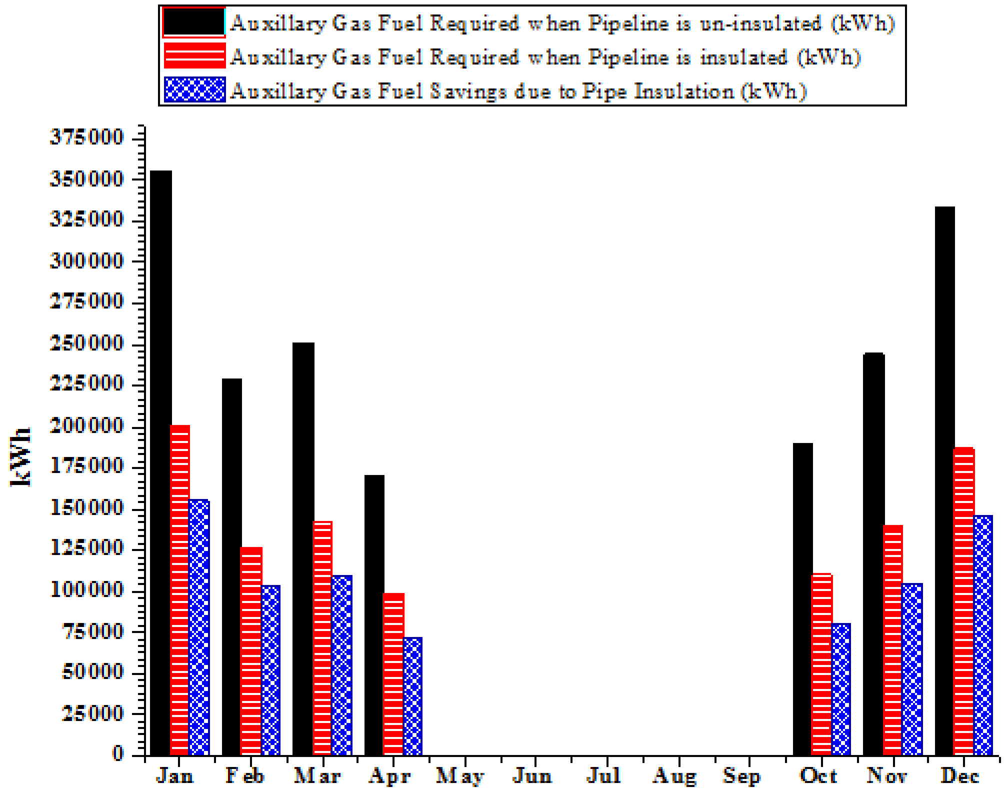

Figure 5.6: Effect of water pipeline insulation on ETSWH system's performance in kWh-natural gas fuel savings achieved

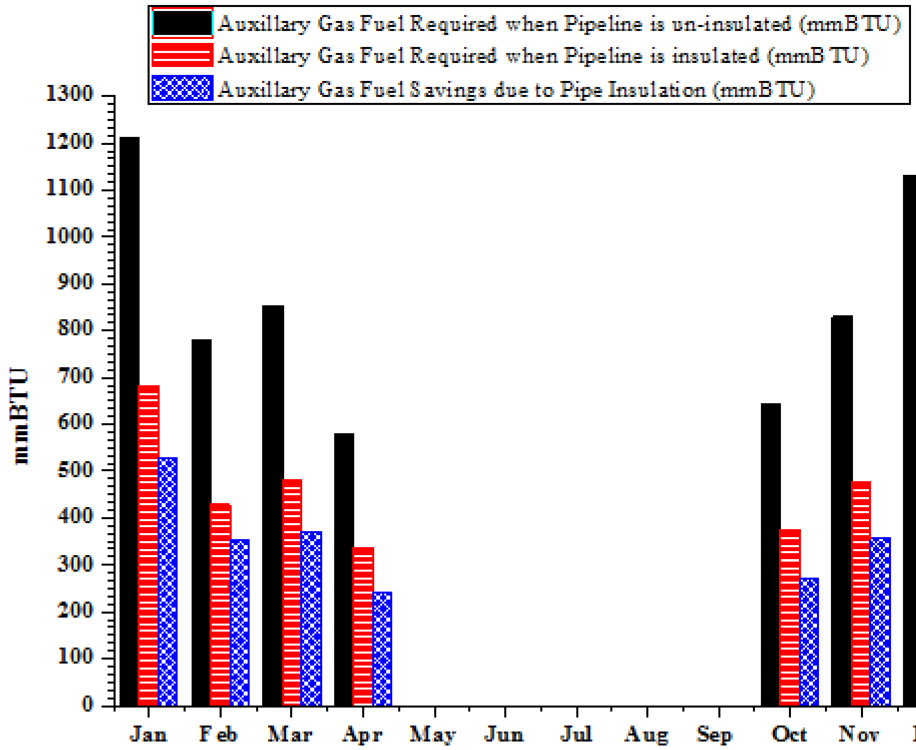

Figure 5.7: Effect of water pipeline insulation on ETSWH system's performance in mmBTU-natural gas fuel savings achieved

Analysis of Figure 5.6 and Figure 5.7 show that effect of pipeline insulation in terms of natural gas fuel savings is larger for a month with low ambient temperature and wind speed values (i.e. for Jan) and is smaller for a month with comparatively high ambient temperature and wind speed values (i.e. for Apr). The reason behind this revealed effect is: a month with low ambient temperature value would lead to large temperature difference (ΔT) between inside flowing hot water and outer air temperature. This ΔT is directly corresponds to heat loss due to conduction phenomena through wall, thus larger ΔT value would result in increased heat losses through pipeline wall and vice versa. So in a scenario with larger ΔT value, pipeline insulation effect would also be greater than a scenario with smaller ΔT value. Consequently greater pipeline insulation effect would result in large reductions in natural gas fuel requirements to attain desired hot water temperature.

5.1.5 Performance Comparison of Hybrid ETSWH and Hybrid FPSWH Systems

Figure 5.8 shows the performance comparison of hybrid ETSWH and hybrid FPSWH systems working under same conditions.

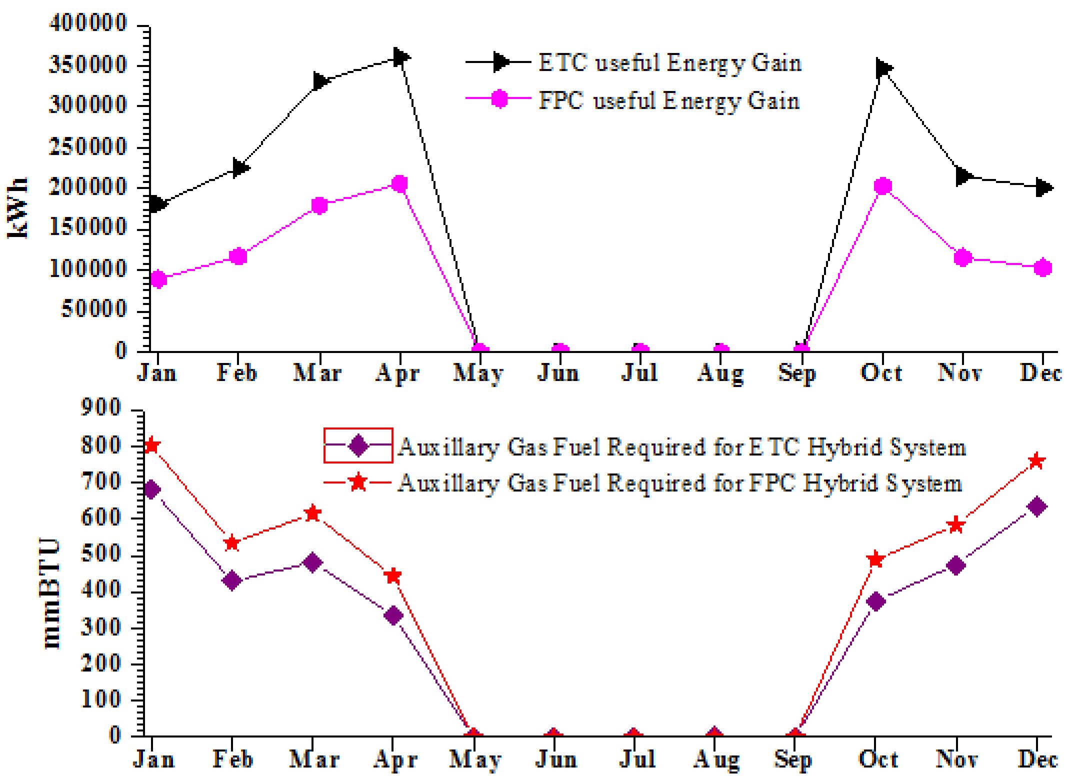

Figure 5.8: Hybrid ETSWH and hybrid FPSWH systems performance comparison in kWh-natural gas fuel savings

Comparison is performed in terms of useful energy produced by solar thermal ETC/FPC and natural gas fuel required by system to fulfill hot water demand. Analysis shows that useful energy value produced by ETC is higher than produced useful energy of FPC as: 50.71% for Jan, 47.07% for Feb, 45.75% for Mar, 42.95% for Apr, 41.42% for Oct, 46.33% for Nov and 48.63% for Dec. Consequently natural gas fuel value required by hybrid FPSWH system to fulfill hot water demand is greater than the requirement of hybrid ETSWH system in following percentages: 17.61% for Jan, 24.49% for Feb, 27.79% for Mar, 31.75% for Apr, 30.54% for Oct, 22.85% for Nov and 19.67% for Dec. Analysis reveals that natural gas fuel values required by hybrid FPSWH system are higher than hybrid ETSWH system requirement and are in accordance with produced useful energy gap between ETC and FPC as; higher the percentage value of useful energy produced by ETC more than FPC, greater would be the natural gas fuel percentage required by hybrid FPSWH system extra than hybrid ETSWH system requirement.

5.2 RETScreen Simulation Based Economic and Environmental Analysis

Economic and environmental analysis of the modelled SWH systems is performed using RETScreen simulation program to figure out the viability of the system installation for domestic hot water application. All parameters affecting the economic and environmental viability of SWH systems and their role in making the project feasible or not in Islamabad-Pakistan are presented in the Figure 5.9. Economics of a project takes into account its financial viability in the terms of NPV, IRR, payback period and BCR [2]. Environmental analysis is carried out on the basis of GHG emissions reductions achieved.

NPV accounts for the time value of future cash flows discounted at certain interest rate by measuring difference between market value of project and its cost [3, 4]. NPV of the system is figured out by using the following relation [3]:

$$-CF_0 + \sum_{i=1}^{t} [\frac{CF_i}{(1+r)^i}] = NPV \tag{5.1}$$

Where; i= 1, 2, 3,….,t

i. If NPV>0, it estimates the project being economically feasible.

ii. If NPV<0 then it is not feasible to accept the project.

If all projects under consideration have positive NPV then the project with higher NPV is more attractive and feasible than that of lower one.

IRR is a form of discounted rate that equals the NPV of a project cash flows to zero [3] and often is used in capital budgeting. It can be calculated by modifying the equation 5.1 as:

$$-CF_0 + \sum_{i=1}^{t} [\frac{CF_i}{(1+r)^i}] = NPV = 0 \qquad (5.2)$$

IRR is thought to be the best alternative economic determinant to NPV for evaluating the financial viability of a certain project. But when we see IRR and NPV in conflicting relation with respect to a project then NPV is thought to be the preferable criteria for analysis [3].

Payback period is an important economic determinant for a project with respect to investor's insight. Payback period tells about the time length to recover initial investment of project. It can be calculated by using a simple mathematical relation of project cost and annual cash flows [3] represented as:

Payback Period= Cost of Project / Annual Cash flows (5.3)

BCR, used in corporate finance sector, is an attempt to describe the quantitative and qualitative relationships between possible benefits and costs of undertaking new projects or replacing the old ones. Greater the BCR, more viable the project is [5].

Comparative economic analysis of hybrid ETSWH and hybrid FPSWH systems, illustrated in Figure 5.9, elaborates that hybrid ETSWH has more economic viability than hybrid FPSWH with greater NPV, IRR and BCR values while lower payback back period. Overall all, both hybrid systems are economically viable to be installed as having positive NPV and BCR values greater than one.

GHG emissions worried the whole world a lot. It remained the most concerned issue during the last decade particularly, that's why many protocols and standards have been set to control the emissions. Analysis of Figure 5.9 shows that installation of hybrid ETSWH and hybrid FPSWH systems will result in 0.5tCO_2 and 0.4 tCO_2 GHG emissions reduction respectively in capital territory of Pakistan.

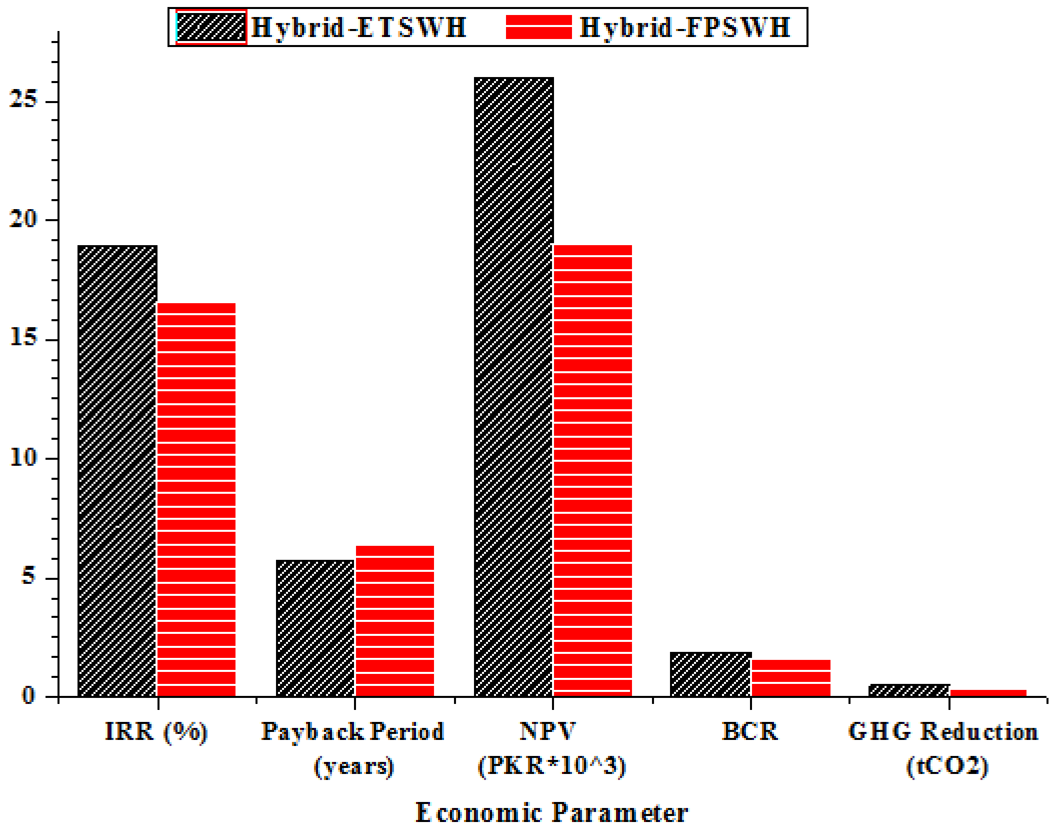

Figure 5.9: Comparative economic and environmental analysis of hybrid ETSWH and hybrid FPSWH systems

5.3 Numerical Model Based Optimization

Performance of solar thermal collector is largely affected by tilt angel position of collector. To find out the optimum tilt angle of solar thermal collector for winter season, numerical model of solar thermal collector is built in m-file user interface of MATLAB program using mathematical relations. Tilt angle based performance of solar collector is optimized considering useful energy of collector as indication parameter as depicted in Figure 5.10 and Figure 5.11. Analysis of Figure 5.10 and Figure 5.11 show that optimum tilt angle of south facing solar thermal collector in Islamabad-Pakistan equals to Lat.+19^{o} for a day during which solar radiations value falling on collector's surface is found minimum (i.e. the coldest day). At this latitude position, useful energy value of solar thermal collector is found maximum.

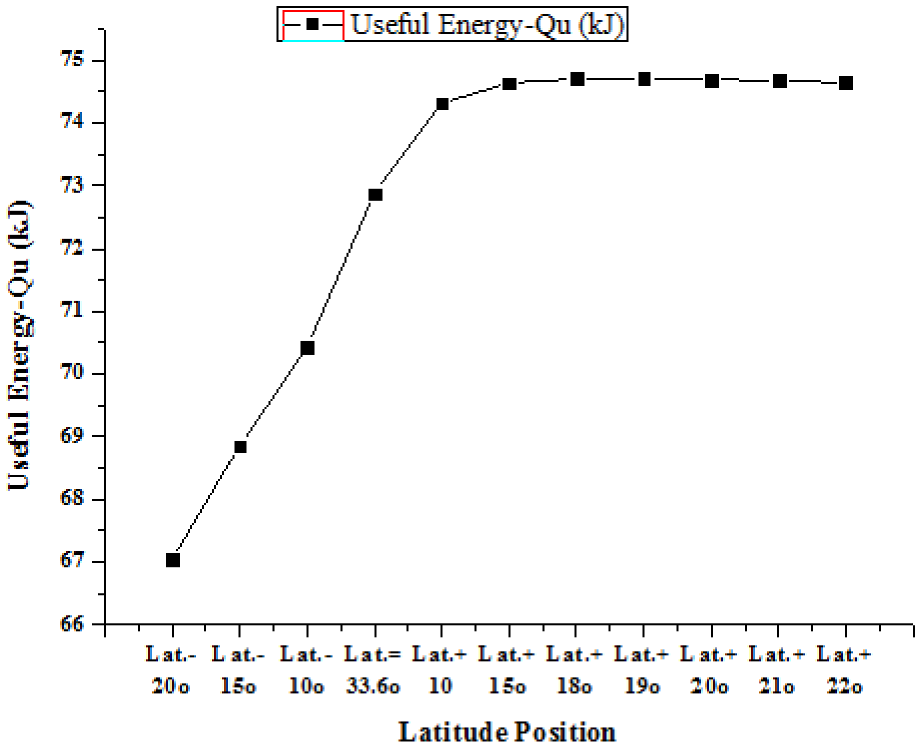

Figure 5.10: Solar thermal collector's tilt angle optimization

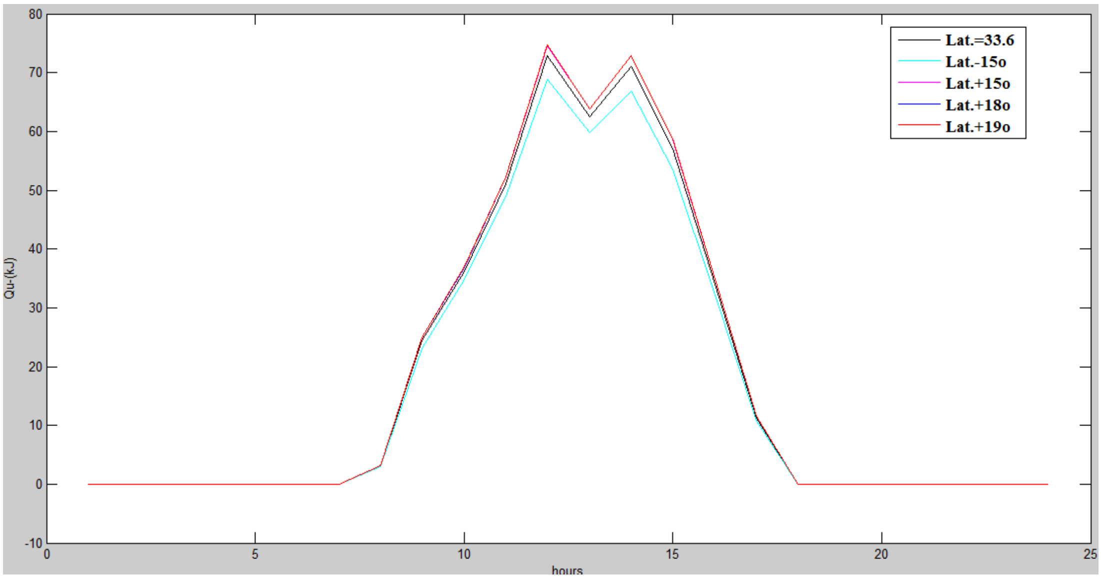

Figure 5.11: MATLAB output for solar thermal collector's tilt angle optimization

5.4 Experimental Results and Comparison with Simulation Outcomes

Experimentation is performed for 17th and 18th of August, 2014. Experimental testing is focused on collector's outlet hot water temperature and global solar irradiance value available on collector's surface. After that experimental values are compared with simulation outcomes as shown in Figure 5.12. Analysis of Figure 5.12 shows that in both, experimentation and simulation, cases available solar irradiance value and collector's outlet hot water temperature parameters show maximum values for 12:00 hours. Comparative analysis revealed that there exists ~5.93% and 5.14% percentage error between experimental and simulation outcomes, noted for peak hour values, for 17th and 18th August 2014 respectively.

- **Back-up Fuel Requirements**

Fuel value required to attain hot water temperature equals to 60^{o}C against 30^{o}C average water inlet temperature, for heating 190Lit water storage tank is determined as shown in Table 5.1.

Table 5.1: Experimental back-up fuel requirement

Fuel Name	**Experimental Fuel Value**
Natural Gas	3.5 kg
Wood Biomass	4.5 kg

Figure 5.12: Comparison between experimental and TRNSYS simulation outcomes

Summary

All results either simulation or experimental are illustrated and discussed here and all conclusions along with recommendations are mentioned in next chapter!

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Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A SWH system is modelled using ETC/FPC in TRNSYS and RETScreen simulation programs for a location of having latitude= 33.6^{o}N and longitude= 73.1^{o}E to study its thermal and economical behavior respectively. Modelled SWH system is hybridized with natural gas water heater for providing backup during non-sunny time and to provide extra required heat energy for attaining desired hot water temperature. Hybrid ETSWH system's performance is evaluated and also compared with hybrid FPSWH system for winter season (Oct to Apr). Numerical model of solar thermal collector is built in MATLAB m-file user interface to optimize the tilt angle based performance of hybrid SWH system. Modelled hybrid SWH system is developed using heat pipe evacuated tube solar thermal manipulate. It is concluded that:

- ETC is much more efficient than FPC as convective and radiation losses are much less because of absence of air in space between absorber and cover sheet and having more solar energy absorbing per unit area volume as compared to FPC.
- Useful energy produced by solar thermal collector is more affected by variations in direct radiation's component of global solar radiations than in diffused radiation's component.
- Using hybrid ETSWH system instead of gas water heater would result in 23-42% seasonal natural gas fuel savings.
- It is found that the presence of differential temperature controller in hybrid ETSWH system, for avoiding overheating and freezing in pipe, could result in 3-10% natural gas fuel savings.
- Furthermore, 2mm PVC water pipeline insulation could lead to 41-44% natural gas fuel savings as result of reduction in thermal heat losses due to conduction

phenomena through pipeline wall during hot water flow from collector/storage tank to end user.

- Performance comparison of hybrid ETSWH and hybrid FPSWH systems revealed that hybrid ETSWH system is much more efficient than hybrid FPSWH system in Islamabad-Pakistan as useful energy value produced by ETC is 41-51% greater than produced by FPC. And natural gas fuel savings could be achieved through implementation of a hybrid ETSWH system are 17-32% higher in value than could be achieved through a hybrid FPSWH system installation.
- TRNSYS model developed and methodology used for current study can be repeated for any location of world for evaluating and comparing the performance of SWH systems.
- Economic determinants i.e. NPV, IRR, payback period and BCR favor hybrid ETSWH system more than hybrid FPSWH with 5.7 years payback period and 1.87 BCR.
- Application of hybrid ETSWH and hybrid FPSWH systems would result in 0.5tCO_2 and 0.4 tCO_2 GHG emissions reduction respectively.
- The optimum tilt angle of south facing solar thermal collector in the capital city of Pakistan equals to Lat.+19^o for winter season.
- For providing back-up, natural gas is more efficient to be used as back-up fuel than wood biomass because of having high heating value.
- Mass flow rate of flowing fluid affects the collector's outlet hot water temperature a lot, as mass flow rate corresponds to the resident time of flowing fluid inside the collector that directly relates to the amount of absorbed useful energy causing increase in flowing fluid temperature.
- Comparison of experimental and simulation outcomes shows that there exists 5-6% percentage error between experimental and simulation resultant values.

SWH technology is need of time for the whole world in energy's future concerns especially for those countries where energy field situation is already disastrous as in Pakistan. This technology will not only help in reducing natural gas fuel consumption (where gas is used for water heating purposes) but also be helpful in overcoming natural gas fuel shortage especially during winter season and in green growth of country.

6.2 Recommendations

The findings of present work show that application of hybrid SWH system could be a milestone for natural gas fuel savings and green growth of country. The recommendations for future work could be suggested as:

- This work can extended for study of SWH systems application in other cities using TRNSYS and RETScreen methodology.
- Water desalination and water storage tank stratification effects can be studied in detail.
- In current work, tilt angle based performance optimization is carried out using numerical model only. This optimization can be performed experimentally using developed set-up.
- Experimentation is performed using ETC only. This work can also be extended for studying the performance of photovoltaic thermal (PV/T) collectors in comparison with ETC/FPC.
- Combustions analysis of furnace fuel combustion process can be analyzed and improved for reducing back-up fuel requirement.
- SWH system can be hybridized with phase change materials (PCMs) that will completely diminish the conventional fuel requirements.

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Performance of Heat Pipe Evacuated Tube Solar Water Heater Hybridized with Natural Gas Fuel

Aamir Mehmood [a],*, Adeel Waqas [a], Waqas Khalid [b]

[a] Centre for Energy Systems, National University of Sciences and Technology Islamabad-44000, Pakistan.

[b] School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology Islamabad-44000, Pakistan.

*aamir.mehmood08@gmail.com

Abstract

Solar thermal water heating is much developed and well-proven renewable energy technology being used in the world. The current study is focused on performance evaluation of solar water heating (SWH) system using non-concentrated solar thermal collector. For this purpose, a TRNSYS simulation model of SWH system is built using heat pipe evacuated tube collector. Modelled water heating system is hybridized with natural gas fuel. Performance of hybrid evacuated tube solar water heating (ETSWH) system is studied on the basis of useful energy produced by solar collector and natural gas fuel savings achieved as a result of replacing gas water heating system with hybrid ETSWH system. It is found that 23-42% natural gas fuel could be saved by replacing hybrid ETSWH system with gas water heating system. Effect of differential temperature controller presence and pipeline insulation is also studied in terms of natural gas fuel savings. Performance of hybrid ETSWH system is also compared with hybrid flat plate solar water heating (FPSWH) system and it is concluded that hybrid ETSWH system is much more efficient than hybrid FPSWH system at the location having latitude= 33.6^{o}N and longitude= 73.1^{o}E (Islamabad-Pakistan).

Keywords: Solar thermal collector, Water heater, TRNSYS, Collector useful energy.

Abbreviations

SWH	Solar Water Heater/Heating
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector

ETSWH	Evacuated Tube Solar Water Heater/Heating
FPSWH	Flat Plate Solar Water Heater/Heating

1. Introduction

Energy is central cohesive force for sustainable development and economic growth. In the recent years, extensive usage of conventional fossil fuels to fulfill energy thirst resulted in two main issues [1]: rapid depletion of fossil fuels reserves and environmental concerns emerged due to combustion of high carbon content crude oil products. These emerging concerns diverted the world's focus towards design and operation of clean energy systems.

Clean energy systems based on renewable energy technologies could play appreciable role in improving energy security and to mitigate environmental concerns by replacing the conventional fuels utilization in four discrete zones like electric power production, transportation of fuels, hot water production and off-grid power services. Renewable energy proportion in global energy mix is continued to increase and has already surpassed the targets in 2010 that were project for 2020 [2]. Renewable energy share of global final energy consumption estimated at end of 2013 is 22.1%, that is 3.1% greater than that of 2012 [2] and is continued to increase significantly.

Among renewable energy technologies, solar seems the more promising one has increased usage rate of ~30% per annum since 1980 [3]. Solar technology has two main usage domains: solar thermal heating/cooling and solar photovoltaic. The economic benefits possible to be attained as result of SWH technology application can be realized through conventional fuel savings achieved and reduction in environmental issues. SWH technology are playing significant role in domestic and industrial sectors of many countries by saving their conventional fuels being used for water heating purpose. Total global installed SWH capacity has increased by 70% and 13.5% in 2013 from 2004 and 2012 respectively [2]. China is leader of global solar thermal market and followings among top five countries are United States, Germany, Turkey and Brazil [2].

In history, the first SWH system prototype called as "Hot Box" was made as result of Swiss naturalist De Saussure's hypothesis in 1767 [4]. But the first US-patented commercial level SWH named “Climax” was made by Clarence M. Kemp in 1891 [5]. Then in early 19^{th} century, many researchers started working on improving the SWH system’s design considering SWH system being segregated in to two major parts: solar thermal collector and storage tank. As result of these struggles in the design improvement, thermosyphon principle was introduced for the first time by William Bailey in 1909 [6]. In 1960 SWH became a commercial product before that it was used for domestic hot water/ space heating applications [7]. In start, flat plate collectors were used in SWH systems, then evacuated tube and concentrated thermal technologies also evolved.

Several researchers studied the SWH collectors using both experimental and theoretical approaches. Hussein [8] developed a modified simulation model for wickless heat pipe flat plate solar collector having cross flow heat exchanger and validated the model in Cairo, Egypt. Azad [9] investigated the thermal behavior of gravity assisted heat pipe solar collector using both experimental and effectiveness-NTU method based theoretical approach. Ayompe et al. [10] developed a TRNSYS model, used in temperate climates for forced circulation SWH systems using FPC and heat pipe ETC and validated it by comparing the modelled and measured data. Banister et al. [11] worked on development of TRNSYS simulation model of solar assisted heat pump and validated the model using experimental setup consists of solar collector, heat pump, storage tank and heat exchanger. Shihabudheen and Arun [1] investigated the performance of hybrid photovoltaic-thermal water heating system installed at Calciut using both experimental and TRNSYS model based analytical approaches and concluded that expected annual solar fraction of system is 0.7261.

2. Aim of the study

Main objective of the current work is to study the thermal performance of SWH system built in TRNSYS simulation program using ETC. TRNSYS Built model is hybridized with natural gas fuel, as ~1.4 million tons of oil equivalent (MTOE) natural gas fuel is consumed for water heating purpose [12] in Pakistan. The focus of present study is;

- To compare the performance of natural gas fuel based water heating system with hybrid ETSWH system, considering useful energy produced by ETC and natural gas fuel savings achieved as deciding parameters.
- To investigate the effect of water pipeline insulation and presence of differential temperature controller, in terms of natural gas fuel savings possible!
- Performance of hybrid ETSWH system is also compared with hybrid FPSWH system operating in same region.

3. Methodology

A domestic scale SWH system is modelled in TRNSYS simulation program using non-concentrated solar thermal collectors for the capital city of Pakistan. Modelled SWH is hybridized with natural gas fuel using a backup gas heater to provide auxiliary heat energy required to attain desired hot water temperature and for continuing hot water supply during non-sunny time if required. System performance is studied considering natural gas fuel savings, an indication parameter, as result of impressive substitutions i.e. installation of hybrid SWH system instead of gas water heater, presence differential temperature controller, water pipeline insulation. Performance comparison of hybrid ETSWH and hybrid FPSWH systems for certain climatic conditions is also studied. The methodology used to evaluate the performance of modelled systems is shown in Fig 1, involving all effective inputs parameters and estimated outcomes of the current study.

3.1 Parameters studied to evaluate the hybrid SWH system

The input parameters studied for analyzing the performance of modelled hybrid SWH system in TRNSYS software are listed in Table 2. Hybrid SWH system is modelled for a house occupied by five family members. Hot water storage tank volume equals to 75gal (~284Lit) is estimated through personal communication and market observations based on people daily hot water usage rate, keeping in view the market availability factor too. Both heating elements of the storage tank are switched off as auxiliary tank heating device running on natural gas fuel is equipped in system for providing backup. Hot water draw-off profile estimated, for domestic usage of a five-member house during winter season months, through interaction with system designers and domestic users is shown in Fig 2. Mass flow rate value of the system is set in accordance with volume of hot water draw-off. Solar thermal collector area value is nominalized through optimization process for the coldest day of the year (1st Jan) according to meteonorm weather data, considering auxiliary natural gas fuel required to meet the demand as indication parameter. To maximize the solar incident radiation value, incident angle modifier setup file provided by TRNSYS database is also inserted in collector's settings. Hot water temperature monitored by differential temperature controller is set equals to 55^{o}C with upper and lower dead band (ΔT) of 5^{o}C. Differential temperature controller also protects the system from overheating and water freezing phenomena. Water pipeline is thermally insulated with 2mm thick PVC coating to reduce the heat losses, could occur due to temperature difference between inside flowing hot water temperature and outside environment.

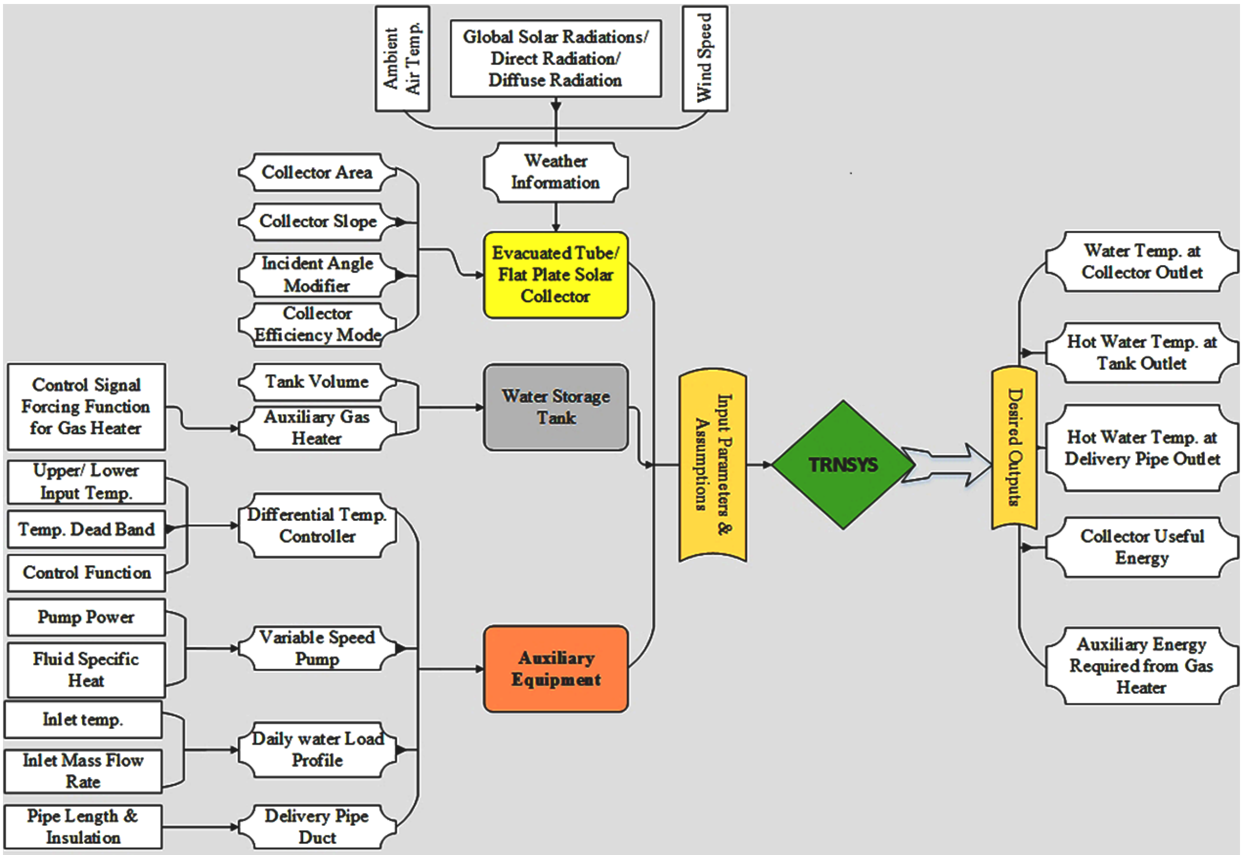

Fig 1: Methodology to evaluate the performance of modelled hybrid SWH system

Table 2: TRNSYS model input parameters

Factor	Value
Household Parameters	
No of Occupants	06

Operating days per week	7
Solar Thermal Collector	
Collector area	1.7 m^2
Type	ETC/ FPC
Fluid Specific heat (for Water)	4.190 kJ/kg.K
Solar tracking mode	Fixed
Storage Tank	
Storage Tank Capacity	75gal (~284Lit)
Differential Temp. Controller	
Monitoring Hot water Temp.	55^{o}C
Upper dead band	5^{o}C
Lower dead band	5^{o}C
Auxiliary Tank Heating Device (Gas Heater)	
Natural Gas Heating Capacity	53600 kJ/kg
Thermal Efficiency	0.85 Fraction

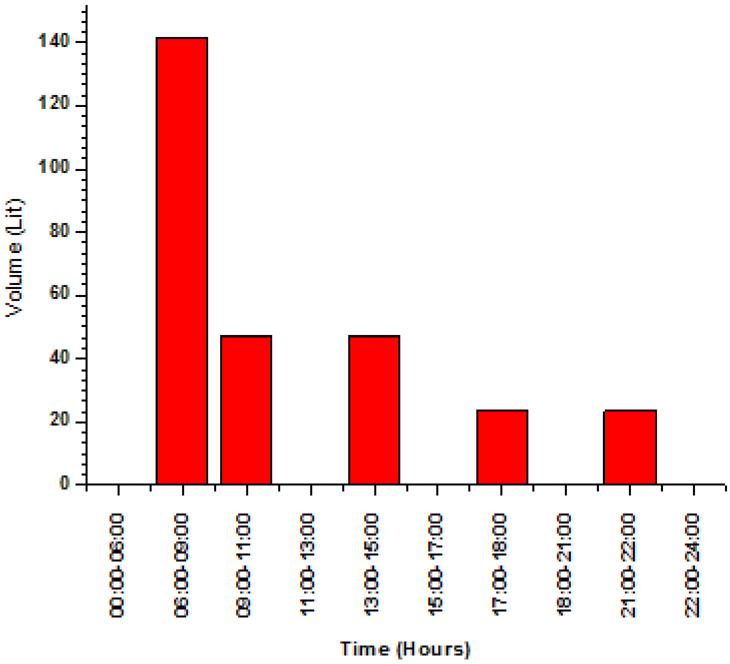

Fig 2: Domestic hot water draw-off profile

3.2 Assumptions used for hybrid SWH system modelling

i) Natural gas is taken as backup fuel as it is the major fuel being used in Pakistan for water heating purpose. It is reported that ~1.4 million tons of oil equivalent

(MTOE) natural gas fuel is consumed for water heating [12] because it is cheaper than liquefied oil products.

ii) Collector slope is adjusted 15^{o} above the latitude of location as system is designed to fulfil hot water demand in winter season [13] (October to April) specifically.

4. Modelling

4.1 TRNSYS model

The hybrid SWH system is modelled using transient systems simulation (TRNSYS) software [14], a quasi-steady state simulation program, considering a TRNSYS validated model developed by Ayompe et al. [10] as a reference. TRNSYS is components based software package having flexible nature that accommodates both the researchers and practitioners regarding ever-changing needs of energy simulation community. TRNSYS software consists of two main parts [15]: engine (called kernel) and extensive library of components. Kernel reads and processes the input files, solves the system iteratively, determines convergence and thermo-physical properties, inverts the matrices, performs linear regression, interpolates external data files and plots the system variables. Regarding extensive library part, each component models the performance of one part of the system. This package enables the user to select and interconnect system's components in desired manner to build up a working system model. TRNSYS model is build up on the basis of desired system's information flow diagram. Information flow diagram of the model built for current study is shown in Fig 3.

Main building component of TRNSYS model is solar radiant heat energy collector which is ETC (type 71) and FPC (type 73). To hybridize the SWH system with conventional fuel for providing backup, auxiliary tank heating device (type 1226-Gas) is connected. Other additional components interconnected to build up a model are: weather information including in-plane solar radiations (global, direct and diffused radiations), wind speed, humidity and air temperature (type 99), hot water draw-off 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 plotter (type 65c).

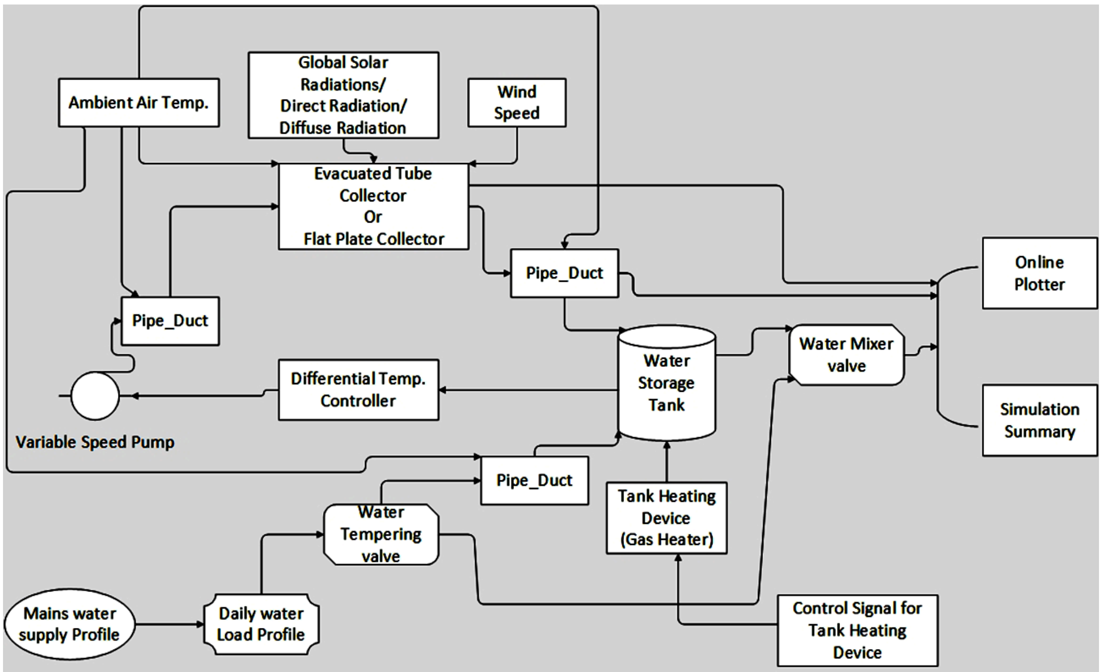

Fig 3: TRNSYS information flow diagram for hybrid SWH system's modelling

4.2 Weather information

Weather conditions are very important parameters for evaluating the system's performance based on renewable energy sources specifically of solar and wind.

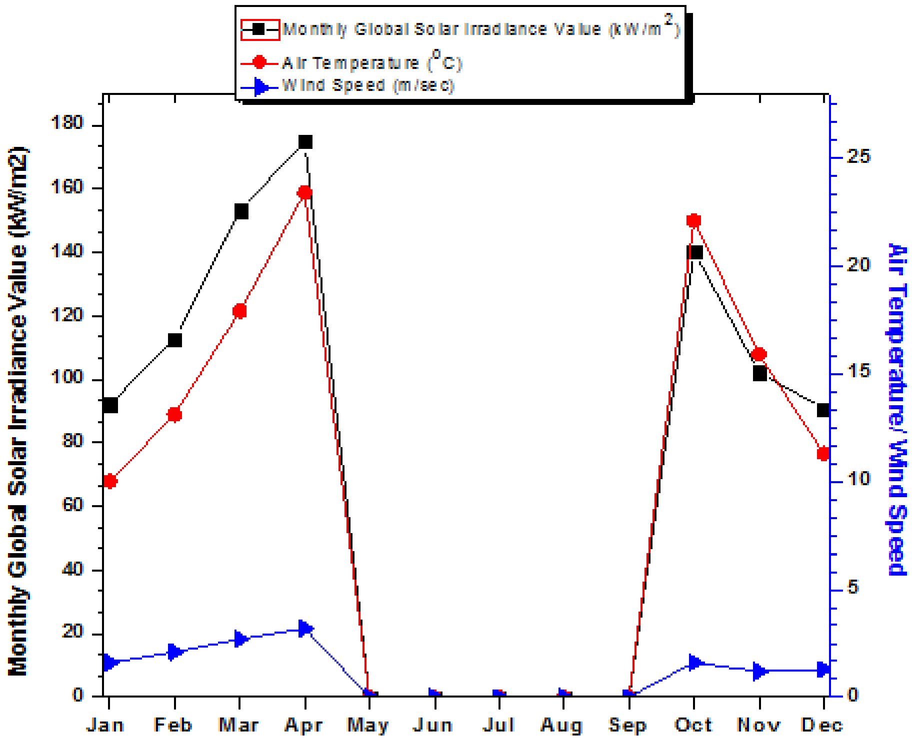

Fig 4: Weather information of winter season of selected location

Weather information of the location having latitude= 33.6^{o}N and longitude= 73.1^{o}E, where we are interested in evaluating the performance of hybrid-SWH system in terms of useful energy produced by solar thermal collector and natural gas fuel savings, are depicted in Fig 4. Weather information including global solar radiation, air temperature and wind speed are plotted for winter season (Oct-Apr) during which hot water is requirement of domestic sector.

5. Results and discussions

Results based on solar collector's useful energy produced and natural gas fuel savings as result of replacing gas water heater with hybrid ETSWH system, presence of differential temperature controller and water pipeline insulation are discussed. Comparison of hybrid ETSWH and hybrid FPSWH systems is also performed and discussed.

5.1 ETC useful energy

Monthly useful energy produced by ETC is plotted against available monthly solar radiations, in Fig 5. It is observed that increase in global solar irradiance value results in increased ETC useful energy value. Analysis of Fig 5 shows that this trend is not followed for month of Jan. In this month, global solar irradiance value increases compared to last month but ETC useful energy produced value decreases. The reason is the global solar radiations mainly consist of two components; direct radiation component and diffused radiation component. Among these direct component has more effective solar thermal energy intensity as compared to diffused component, that's why higher the value of direct component would result in greater value of useful energy produced by solar collector. As analysis shows that on moving from Dec to Jan, monthly global solar irradiance value increases by 1.42% but there is 10.02% decrease in ETC useful energy produced value. The reason of this effect is; decrease in direct component of global solar radiations by 33.4% rather than being increased with increase in global solar irradiance value. While for remaining months, increase in global solar irradiance value accompanies the increase in direct radiation component that consequently results in higher useful energy produced value with respect to last month and vice versa.

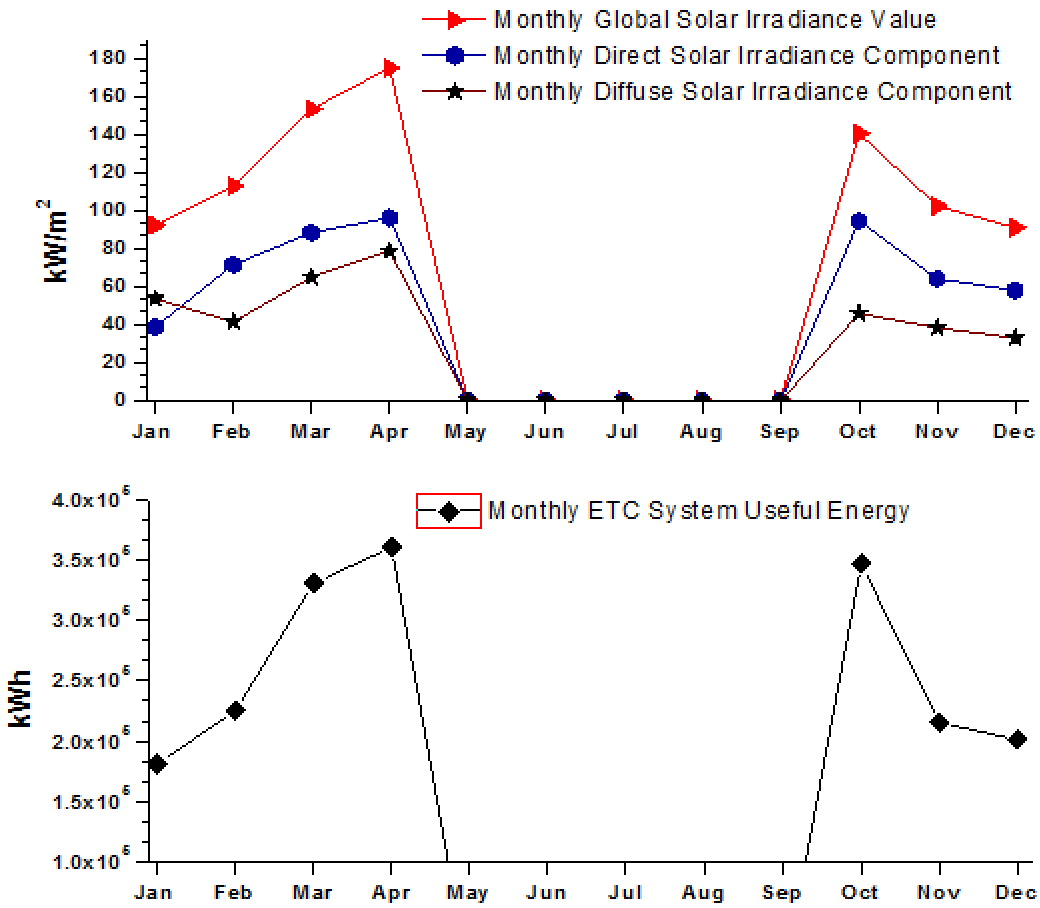

Fig 5: Monthly useful energy produced by ETC

5.2 Hybrid ETSWH system

Natural gas fuel is one of the major conventional fuels being consumed for water heating purpose during winter season in Pakistan. That's why we come across severe natural gas shortage issue instead of having one of the world's largest natural gas reserves called as "Sui". Results plotted in Fig 6 depict that how much natural gas fuel could be possibly saved by replacing gas water heater with hybrid ETSWH system. Hybrid ETSWH system consists of ETC and gas heater to provide backup for non-sunny time. Analysis of Fig 6 shows that monthly natural gas fuel savings possible are: 23.58% (for Jan), 31.15% (for Feb), 35.41% (for Mar), 41.49% (for Apr), 41.47% (for Oct), 30.37% (for Nov) and 25.98% (for Dec). Results elaborate that natural gas fuel savings achieved for Apr month has highest value while for Jan month has lowest value. The reason is; higher the value of useful energy produced by ETC, greater would be the natural gas fuel savings (affirmed by analysis of Fig 5 and Fig 6). Natural gas fuel savings are also linked with air temperature; lower the value of air temperature leads to smaller solar irradiance value (i.e. lower solar thermal collector's useful energy produced value), so greater would be the value of natural gas fuel required to fulfill hot water demand and consequently less natural gas fuel savings would be possible.

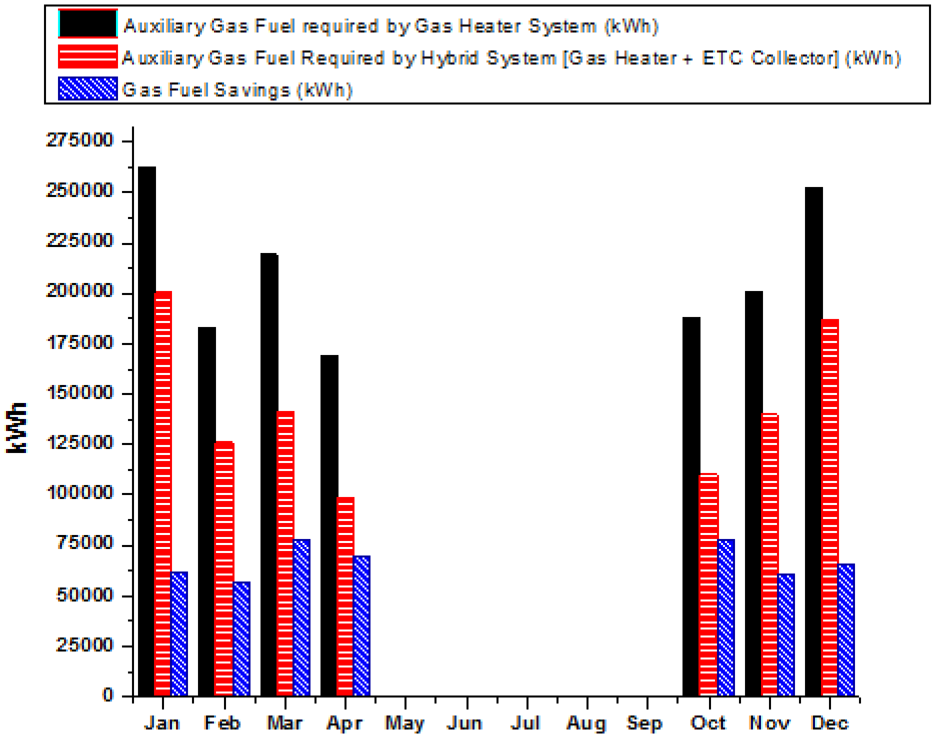

Fig 6: Natural gas fuel savings as result of replacing gas water heating system with hybrid ETSWH system

5.3 Differential temperature controller presence effect on hybrid ETSWH system performance

Differential temperature controller increases the operating efficiency of a heating system. It controls the water circulation system based on temperature difference between storage tank and solar thermal collector. It also monitors the temperature of water delivered at user end keeping in view the set point temperature along with upper and lower dead band. Results plotted in Fig 7 elaborate how much natural gas fuel savings are possible through insertion differential temperature controller in hybrid ETSWH system because this controller provides protection against overheating and freezing to pipe. Analysis of the Fig 7 interprets that 9.32% (for Jan), 8.38% (for Feb), 5.39% (for Mar), 3.16% (for Apr), 4.58% (for Oct), 6.63% (for Nov) and 8.77% (for Dec) monthly natural gas fuel savings are possible due to differential temperature controller presence. Percentage effect of controller presence is smaller for a month in which less value of natural gas fuel is required and vice versa. The reason behind this observed effect is available value of useful energy; higher the value of useful energy available, less natural gas fuel amount would be required and consequently smaller would the effect of differential temperature controller presence in terms of natural gas fuel savings achieved.

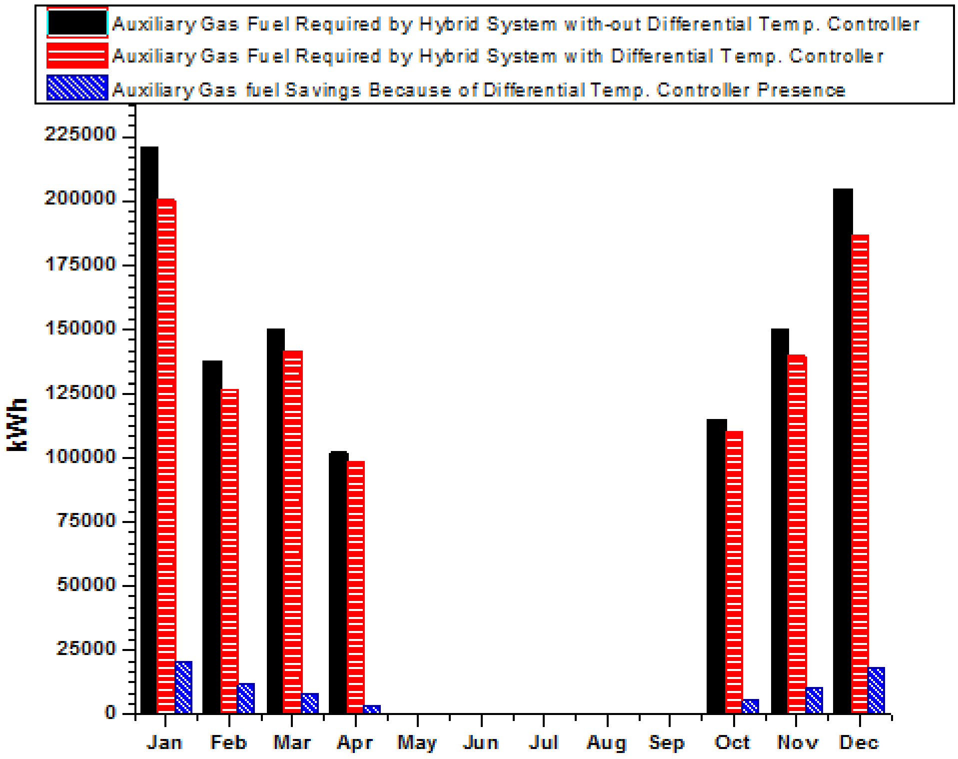

Fig 7: Differential temperature controller presence effect on hybrid ETSWH system's performance

5.4 Water pipeline insulation effect 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 pipeline, heat transfer takes place between inside flowing hot water and outside ambient through conduction phenomena because of temperature difference. To reduce the heat losses due to conduction through pipeline wall, a 2mm polyvinyl chloride (PVC) insulation coating is used resulted in 42.56% [16] reduction in heat loss co-efficient for a location having average wing speed equals to 2.4m/sec. Effect of water pipeline insulation in terms of reduction in natural gas fuel requirement to achieve the desired hot water temperature is: 43.66% (for Jan), 43.47% (for Feb), 42.97% (for Mar), 41.82% (for Apr), 42.03% (for Oct), 42.80% (for Nov) and 42.86% (for Dec) as plotted in Fig 8. Analysis of Fig 8 shows that effect of pipeline insulation in terms of natural gas fuel savings is larger for a month with low ambient temperature and wind speed values (i.e. for Jan) and is smaller for a month with comparatively high ambient temperature and wind speed values (i.e. for Apr). The reason behind this revealed effect is: a month with low ambient temperature value would lead to large temperature difference (ΔT) between inside flowing hot water and outer temperature. This ΔT is directly corresponds to heat loss due to conduction phenomena through wall, thus larger ΔT value would result in increased heat losses through pipeline wall and vice versa. So in a scenario with larger ΔT value, pipeline insulation effect would also be greater than a scenario with smaller ΔT value. Consequently greater pipeline insulation effect would result in large reductions in natural gas fuel requirements to attain desired hot water temperature.

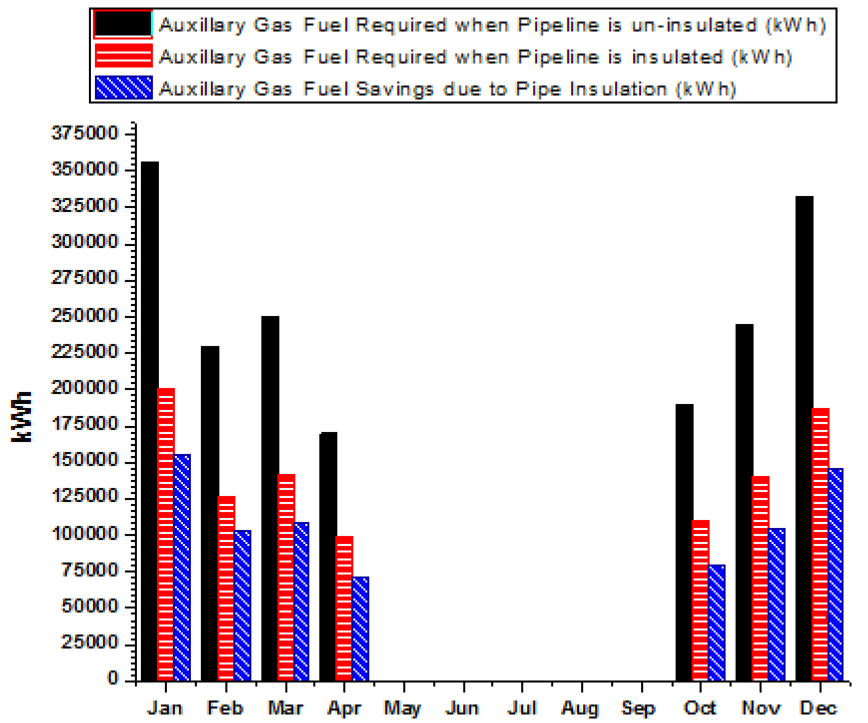

Fig 8: Effect of pipeline insulation in terms of natural gas fuel savings

5.5 Hybrid ETSWH and hybrid FPSWH systems performance comparison

Fig 9 shows the performance comparison of hybrid ETSWH and hybrid FPSWH systems working under same conditions. Comparison is performed in terms of useful energy produced by solar thermal ETC/FPC and natural gas fuel required by system to fulfill hot water demand. Analysis shows that useful energy value produced by ETC is higher than produced useful energy of FPC as: 50.71% for Jan, 47.07% for Feb, 45.75% for Mar, 42.95% for Apr, 41.42% for Oct, 46.33% for Nov and 48.63% for Dec. Consequently natural gas fuel value required by hybrid FPSWH system to fulfill hot water demand exceeds than the requirement of hybrid ETSWH system, in following percentages: 17.61% for Jan, 24.49% for Feb, 27.79% for Mar, 31.75% for Apr, 30.54% for Oct, 22.85% for Nov and 19.67% for Dec. Analysis reveals that natural gas fuel values required by hybrid FPSWH system are higher than hybrid ETSWH system requirement and are in accordance with produced useful energy gap between ETC and FPC as; higher the percentage value of useful energy produced by ETC more than FPC, smaller would be the natural gas fuel percentage required by hybrid FPSWH system extra than hybrid ETSWH system requirement.

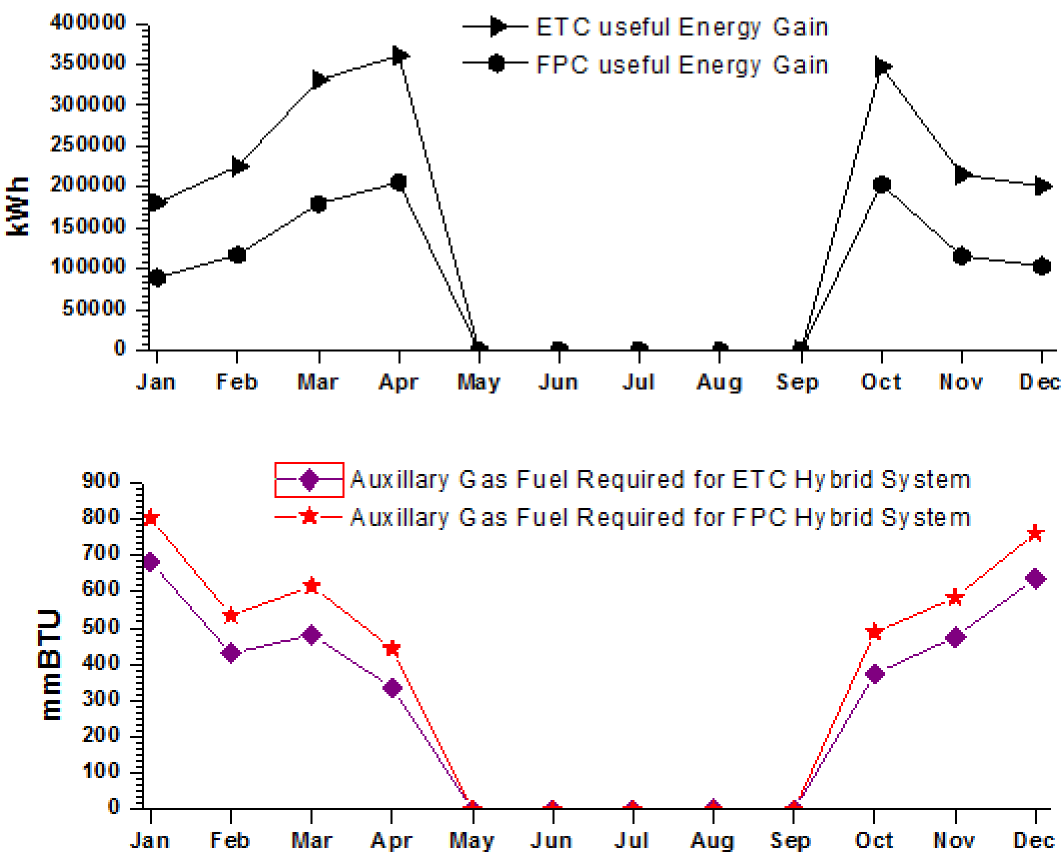

Fig 9: Hybrid ETSWH and hybrid FPSWH systems performance comparison

Conclusions

A SWH system is modelled using ETC in TRNSYS simulation software for a location of having latitude= 33.6^{o}N and longitude= 73.1^{o}E. Modelled SWH system is hybridized with natural gas fuel water heater for providing backup during non-sunny time and to provide extra required heat energy for attaining desired hot water temperature. Hybrid ETSWH system's performance is evaluated and also compared with hybrid FPSWH system for winter season (Oct to Apr). It is concluded that:

- Useful energy produced by solar thermal collector is more affected by variations in direct radiation's component of global solar radiations than in diffused radiation's component.
- Using hybrid ETSWH system instead of gas water heater would result in 23-42% seasonal natural gas fuel savings.
- It is found that the presence of differential temperature controller in hybrid ETSWH system, for avoiding overheating and freezing in pipe, could result in 3-10% natural gas fuel savings.
- Furthermore, 2mm PVC pipeline insulation could lead to 41-44% natural gas fuel savings as result of reduction in thermal heat losses due to conduction phenomena through pipeline wall during hot water flow from collector/storage tank to end user.
- Performance comparison of Hybrid ETSWH and Hybrid FPSWH systems revealed that hybrid ETSWH system is much more efficient than hybrid FPSWH system in Islamabad-Pakistan as useful energy value produced by ETC is 41-51% greater than produced by FPC. And natural gas fuel savings could be achieved through implementation of a hybrid ETSWH system are 17-32% higher in value than could be achieved through a hybrid FPSWH system installation.
- TRNSYS model developed and methodology used for current study can be repeated for any location of world for evaluating and comparing the performance of SWH systems.

SWH technology is need of time for the whole world in energy's future concerns especially for those countries where energy field situation is already disastrous as in Pakistan. This technology will not only help in reducing natural gas fuel consumption (where gas is used for water heating purposes) but also be helpful in overcoming natural gas fuel shortage especially during winter season and in green growth of country.

Acknowledgement

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Techno-economic Evaluation of Flat Plate Solar Collector for Domestic Water Heating Application in Different Climates: A Comparative Study for Pakistan

Aamir Mehmood[a,*], Adeel Waqas[b], Hafiza Tahira Mahmood[c]

[a,b] Solar Energy Laboratory, Center for Energy Systems, National University of Sciences and Technology, Islamabad-44000, Pakistan

[c] Department of Physics, University of Punjab, Lahore-54000, Pakistan

*aamir.mehmood08@gmail.com, [b]adeelwaqas@ces.nust.edu.pk

Abstract

The current article is focused to evaluate techno-economic viability of flat plate solar water heating (FPSWH) technology for domestic users of Pakistan living in different climatic conditions where natural gas is commonly used for heating the water. Evaluation is carried out for six major cities of Pakistan using RETScreen software and results show that FPSWH system with one collector provides 43% solar fraction at a location having Lat. = 30.3^{o}N which is found to be the most economically feasible region than others. Financial viability of FPSWH system is evaluated on the basis of project economics i.e. net present value, payback period, internal rate of return, benefit coast ratio. Environmental analysis predicts about greenhouse gases emissions reduction possible. Technical analysis reveals that the natural gas savings would be possible at different geographical locations through FPSWH system installation, working at 50-80% accumulative solar fraction for a family house. Also it is observed that the payback period of the SWH system for different locations of Pakistan varies between 4.5 to 6.5 years based on the savings achieved from reduced usage of the natural gas.

Keywords: Renewable energy, Flat plate solar water heating, RETScreen, Solar Fraction, NPV

1. Introduction

Sustainability is the major concern in present era. The sustainable economic development of a country is based on energy sector's growth and its efficient utilization. Over the past decade, global primary energy consumption has grown by

30% and would grow by 56% in 2010 to 2040 [1]. In prevailing energy crisis, the whole world especially developing countries are facing two major energy field related issues; to fulfil the increasing energy demand for retaining their existence and the environmental concerns [2] emerging due to extensive use of high carbon content fossil fuels. With aim of minimizing the gap between energy supply and consumption and promoting green growth, a lot of focus has been given in utilizing renewable resources globally and Germany is a leading country in utilizing its solar renewable energy potential.

Pakistan is one of the developing countries where people in urban areas are facing 10-12 hours load shedding while in rural areas this load shedding period is 16-18 hours [3] due to extensive energy shortfall. A significant portion of energy supply is provided through combustion of fuel resources that have limited predicted storage life in world reserves like petroleum and natural gas. Although it is evidential that Pakistan is among the top nature's gifted countries having available renewable energy resources in form of hydro, solar, wind etc. [4]. Among these renewable energy resources, solar energy reaching the earth surface from natural source i.e. sun has huge and indefinite potential [5] that can be exploited in many forms like electricity production, thermal water and space heating.

Current evaluative study aims to have a detail analysis of FPSWH system installation potential in six regions of Pakistan having different climatic conditions. In this perspective, FPSWH system is modelled in RETScreen software using metrological data reported by NASA for six major locations of Pakistan having Lat.: 24.9^{o}N (Karachi), 31.5^{o}N (Lahore), 33.6^{o}N (Islamabad), 34.0^{o}N (Peshawar), 30.3^{o}N (Quetta) and 35.9^{o}N (Gilgit). Present work is focused:

- To analyse the financial viability based on economic determinants i.e. NPV, IRR, BCR and payback period.
- To evaluate the performance of modelled FPSWH system on the basis of technical parameters i.e. solar fraction of system and useful heat energy delivered value.
- It is also revealed that how much backup fuel (natural gas fuel) could be saved and GHG emissions reduction could be possible through modelled FPSWH system installation?

2. Geographical Location of Pakistan

Pakistan is situated on the world map in northern hemisphere positioned at 24^o-37^oN latitude and 61^o-76^oE longitude. Country has five provinces named: Balochistan, Gilgit Baltistan, Khyber Pukhtoon kha, Punjab and Sindh. On average, global solar insolation value in Pakistan is 5-7 kWh/m^2/day [4] and annual global irradiance value is 1900-2200 kWh/m^2 [6] that can be exploited to fulfil the energy needs of people. Fig 10 shows solar radiation map of Pakistan [7].

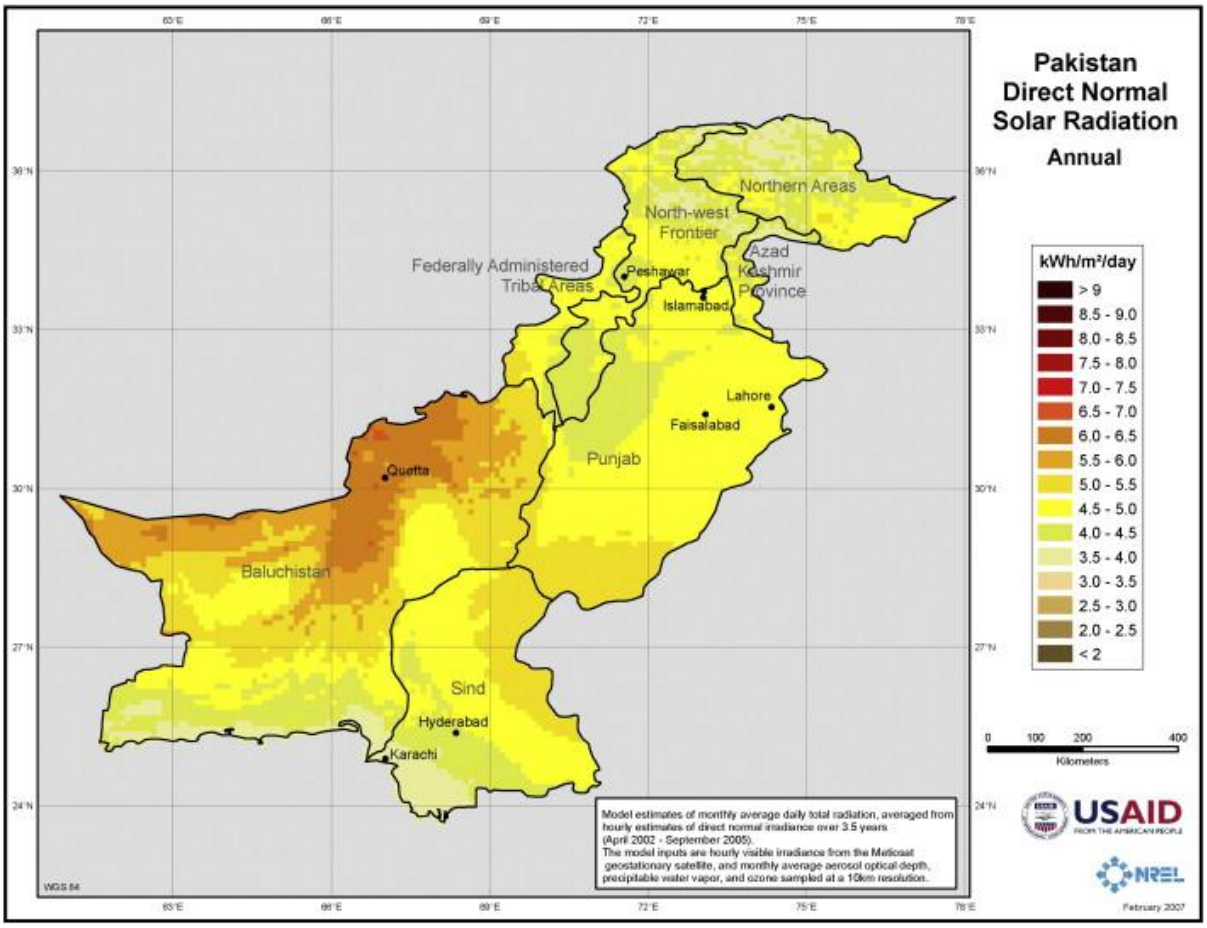

Fig 10: Solar radiation map of Pakistan

3. Climatic Data of the Selected Cities of Pakistan Used for the Current Study

RETScreen software database incorporates city based climatic information in the form of latitude, longitude, location elevation, heating design temperature, cooling design temperature and earth temperature amplitude of the different cities of world reported by NASA. Software also imports detail values of air temperature, relative humidity, daily solar radiation-horizontal, atmospheric pressure, wind speed and ambient temperature reported on monthly and annual basis by NASA. FPSWH system is analysed for six major cities of Pakistan including the federal capital Islamabad and five provincial capitals (shown on Pakistan map in Fig 11 [8]). Since the performance of SWH system is function of solar radiations falling on absorbing surface which depend upon geographical and climatic conditions of a region, so climatic information of map marked cities (in Fig 11) are tabulated in Table 3.

Fig 11: FPSWH project locations selected for current study

Table 3: Climate data of FPSWH project sites in Pakistan

Property	**Climatic data of the cities**					
Location	**Karachi**	**Lahore**	**Islamabad**	**Peshawar**	**Quetta**	**Gilgit**
Latitude (°N)	24.9	31.5	33.6	34.0	30.3	35.9
Longitude (°E)	67.1	74.4	73.1	71.5	66.9	74.3
Ambient temperature (Annual) °C	26.1	24.4	21.6	22.7	18.0	-1.1
Daily solar radiations-horizontal (Annual) kWh/m^2/d	5.34	4.68	4.02	5.16	5.46	4.57

Focus of current study is to evaluate the viability of FPSWH system in different climatic conditions of Pakistan as affirmed by geographical and climatic information. Among climatic information, daily solar radiations falling on the horizontal surface favours Quetta city the most for solar applications as having maximum available value while in Islamabad solar irradiance value is minimum.

4. Methodology to Evaluate the Performance of FPSWH System

SWH system feasibility for a certain region of world map can be examined through system performance evaluation based on energy savings estimation and financial analysis [9] using RETScreen software. RETScreen software based on f-chart method, developed by Natural Resources Canada’s CANMET Energy Diversification Research Laboratory (CEDRL) [10], is used worldwide to figure out the viability of potential renewable energy based projects at the first [10,11]. RETScreen software database has been made using algorithms retaining weather information reported by NASA, cost estimation, product information, online manuals, a website and project case studies [11]. RETScreen software can be used to evaluate the technical, financial and environment viability of an energy project model on the basis of percentage solar fraction, NPV, IRR, payback period, BCR and GHG emissions reduction factors preferentially [11]. The f-chart method designed on utilizability concepts could be used in predicting SWH system’s performance within 1.1% of simulation outcomes for domestic SWH and 4.2% for liquid space heating [12].

A typical household level small-scale FPSWH case study system is modelled in RETScreen software. RETScreen heating project model is used for the calculation of energy production, economics based life cycle assessment, GHG emissions reduction and backup fuel savings through FPSWH system application in domestic sector of Pakistan. The methodology used to evaluate the performance of FPSWH system at different geographical locations of Pakistan is shown in Fig 12; involving all inputs parameters and estimated outcomes of current study.

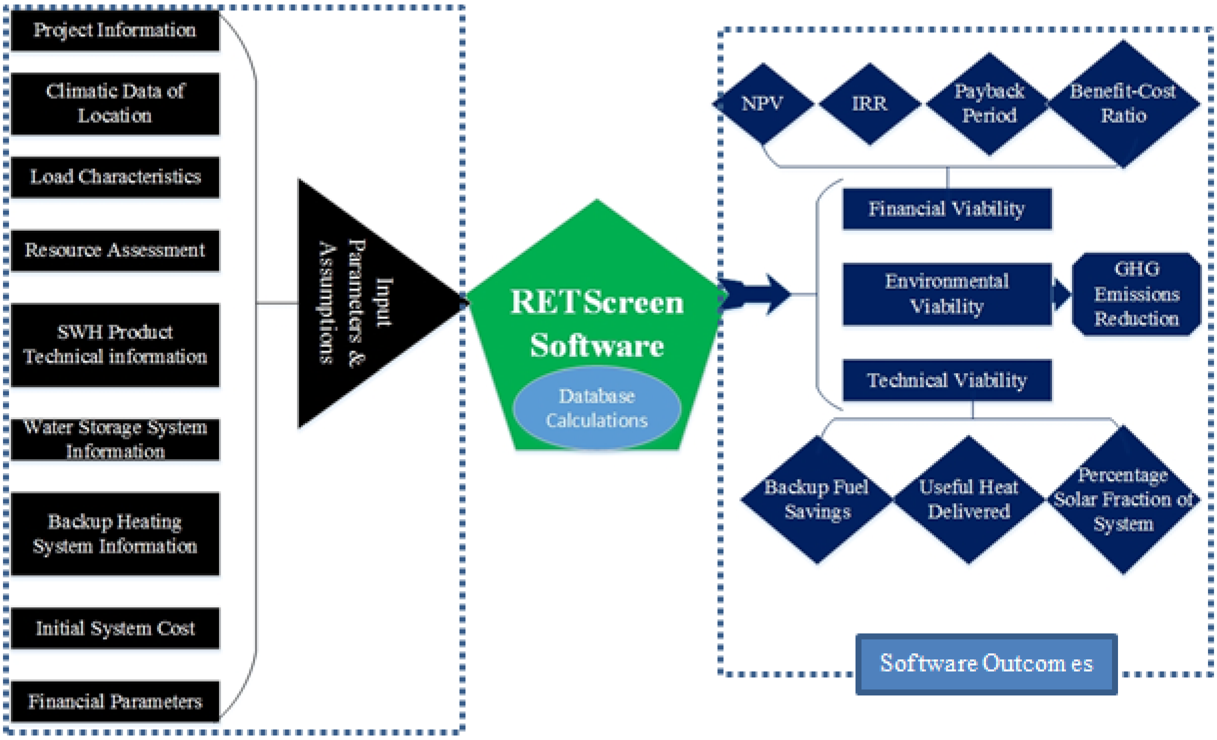

Fig 12: Methodology to evaluate the performance of modelled FPSWH system

4.1 SWH System for the Domestic Sector

Energy resources utilization for water heating purpose is an important segment of energy consumption in domestic sector of Pakistan where majority use natural gas fuel [13] as heating source. While SWH system installation is more appropriate and better option than gas heaters. SWHs operation results in very promising cost effective performance [14] and reduced air pollutant emissions due to substitution of conventional fossil fuels with green energy resource. SWH systems, based on thermo-syphon principle, work using heat transfer fundamentals [12]. SWH systems have solar collector/s in form of glazed flat plate, evacuated tube or unglazed solar heat energy collecting surfaces as their main assembly component [12].

In current study, a typical thermo-syphon type FPSWH system, consists of storage tank and solar collector(s), is modelled (shown in Fig 13). Flat plate collectors also known as mid-temperature solar collectors are efficient to attain required hot water temperature i.e. 60°C [15]. FPSWH collector is the one having insulated enclosure to reduce heat energy loss from back surface with single or double glazed layer/s of special transparent glass at top surface manufactured to extract maximum possible amount of thermal energy from solar radiations falling on collector occupied area [15].

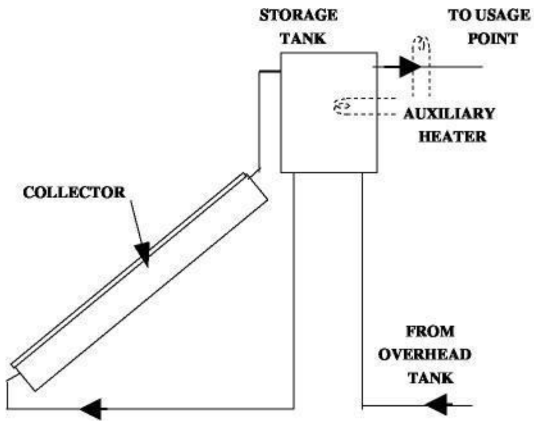

Fig 13: Schematic of thermo-syphon SWH system

Selection of specific FPSWH collector model among different manufacturers depends upon its parameters in terms of which they are differentiated and characterized from RETScreen software database. These collector parameters include gross/aperture area of solar collector, Fr(τα) and FrU_L coefficients. Gross area and aperture area per flat plate solar collector of the model, selected on the basis of optimal ranges of differential parameters keeping in view the concern of availability in Pakistan, are 2.57 m^2 and 2.2 m^2 respectively. Fr(τα) is dimensionless parameter that indicates collector's absorbed energy and depends upon optical characteristics of FPSWH collector with optimum values lay in 0.50-0.90 range [12]. The selected solar collector has 0.68 Fr(τα) value exists in optimal range with maximum optical efficiency and minimum corresponding thermal losses. And FrU_L coefficient is used to characterize the collector's thermal energy losses [$(W/m^2)/^0C$] [12]. Its value varies from 3.50-6.00 $(W/m^2)/^0C$ optimally for the flat plate collectors [12].

SWH thermal capacity of flat plate collector model is calculated by multiplying the total aperture area of collector (m^2) with conversion factor 0.7 that gives total outcome capacity in kW_{th}/m^2 [16]. Thermal capacity of FPSWH system is largely pretended by solar fraction (f) of the system that is given by equation 1 [12].

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (1)$$

In equation.1; X and Y, two dimensionless parameters in terms of which solar fraction is calculated, are represented by equation 2&3 [12] respectively.

$$X = \frac{A_c * FrU_L(T_{ref} - T_a)}{L} \quad (2)$$

$$Y = \frac{A_c * Fr(\tau\alpha) * H_T * N}{L} \tag{3}$$

And efficiency (η) of flat plate collector is given by equation 4 [12,15];

$$\eta = \frac{Q_U}{A_P} * I_T = Fr(\tau\alpha) - FrU_L * \frac{(T_i - T_a)}{I_T} \tag{4}$$

Solar fraction (f) of modelled FPSWH system in certain climate directly corresponds to region's high and low ambient temperatures. Monthly average solar radiations-horizontal falling at six selected locations of Pakistan where we are interested in evaluating the case study system, with corresponding monthly average (years on record: 2000-2013) maximum and minimum ambient temperatures are depicted in Fig 14.

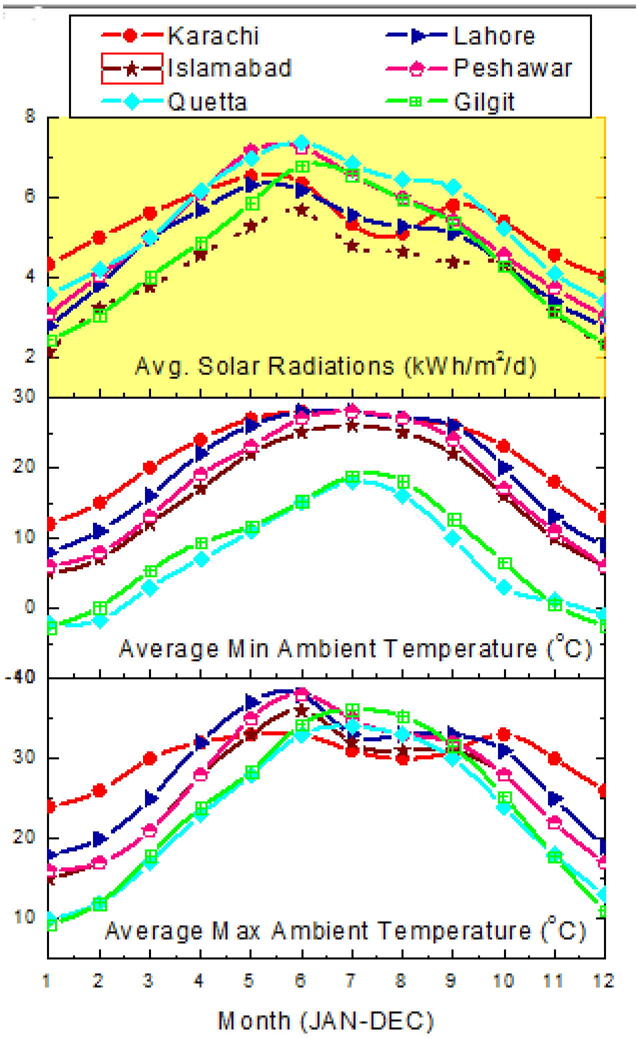

Fig 14: Monthly average solar radiations-horizontal with corresponding maximum (max) and minimum (min) ambient temperature at FPSWH project sites

4.2 Parameters Studied to Evaluate the FPSWH Performance

The input parameters used in analysing FPSWH case study system in RETScreen software, are listed in Table 4. FPSWH system is modelled for a house occupied by six members. Occupancy rate of 80% for the whole week is estimated through personal communication with engineers and SWH system designers, at standard hot water usage rate of 48 L/d/person [17] at 60^{o}C [12,17] for the domestic applications. Nominal value of storage capacity per solar collector area is taken 75L/m^2 as proposed by RETScreen database for flat surface SWH collectors [18] on the basis of f-chart method. Solar fraction (i.e. percentage heat energy load delivered by SWH system) of a SWH system should be in 50-80% range to be economically feasible [18]. As beyond 50-80% SWH system solar fraction range, increase in the percentage solar fraction value due to addition of each solar collector in SWH system is too small at certain locations and SWH system becomes economically infeasible.

Financial input parameters required by software to figure out the viability of FPSWH system involves; average fuel cost escalation rate that is 4.10% [19] in Pakistan, average inflation rate equals to 7.75% [19], discount rate has been raised to 9.5% [20] by State Bank of Pakistan and interest rate currently exists in bank trading is 9.00% [20,21].

Table 4: RETScreen energy model input parameters

Factor	Value
Household Parameters	
No of Occupants	06
Occupancy rate	80%
Daily hot water use	288 L/d
Hot water Temperature	60^{o}C
Operating days per week	7
Resource assessment	
Solar tracking mode	Fixed
Solar water Heater	
Type	Flat plate
Number of collectors	2
Storage Capacity/ Solar Collector Area	75 L/sq. m

Financial Parameters	
Fuel Cost Escalation Rate	4.10%
Inflation Rate	7.75%
Discount Rate	9.5%

4.3 Assumptions Used for FPSWH System Modelling in RETScreen

i. Natural gas fuel is taken as backup fuel because it is the major fuel being used in Pakistan for water heating purpose. Reports reveal that ~1.4 million tons of oil equivalent (MTOE) natural gas fuel is consumed through gas water heaters [13] as it is a cheaper fuel than liquid oil products.

ii. Collector slope is adjusted 15^{o} above the latitude of corresponding location as system is designed to fulfil hot water demand in winter season [15] (from October to March) specifically.

iii. Heating value of fuel assumed is lower heating value, also known as latent heat of vaporization of water in reaction products.

iv. Water freezing factor is ignored in current study that’s why no anti-freezing agent is used for negative ambient temperature regions.

5. Results and Discussions

Results based on system solar fraction, useful heat energy delivered, backup fuel savings, project NPV, IRR, equity and simple payback periods, BCR and GHG emissions reduction are presented and discussed in this section. These results are discussed in the following manner:

i. Economic Analysis
ii. Technical Analysis
iii. Environmental Analysis

5.1 Economic Analysis

Economic analysis of the modelled FPSWH system is performed using RETScreen software to figure out the financial viability of the system installation for domestic hot water application. All economic determinants affecting the financial viability of FPSWH system and their role in making the project feasible or not in different climatic conditions of Pakistan are presented in the Fig 15, Fig **16**, Fig **17** & Fig **18**. Economic analysis of a project takes into account its financial viability in the terms of NPV, IRR, payback period and BCR [22].

NPV accounts for the time value of future cash flows discounted at certain interest rate by measuring difference between market value of project and its cost [23,24]. NPV of the system is figured out by using the following equation [24]:

$$-CF_0 + \sum_{i=1}^{t}[\frac{CF_i}{(1+r)^i}] = NPV \tag{5}$$

Where; i= 1, 2, 3,….,t

iii. If NPV>0, it estimates the project being economically feasible.

iv. If NPV<0 then it is not feasible to accept the project.

If all projects under consideration have positive NPV then the project with higher NPV is more attractive and feasible than that of lower one.

IRR is a form of discounted rate that equals the NPV of a project cash flows to zero [24] and often is used in capital budgeting. It can be calculated by modifying the equation 5 as;

$$-CF_0 + \sum_{i=1}^{t}[\frac{CF_i}{(1+r)^i}] = NPV = 0 \tag{6}$$

IRR is thought to be the best alternative economic determinant to NPV for evaluating the financial viability of a certain project. But when we see IRR and NPV in conflicting relation with respect to a project then NPV is thought to be the preferable criteria for analysis [24].

Payback period is an important economic determinant for a project with respect to investor's insight. Payback period tells about the time length to recover initial investment of project. It can be calculated by using a simple mathematical relation of project cost and annual cash flows represented by equation 7 [18];

Payback Period= Cost of Project / Annual Cash flows (7)

BCR, used in corporate finance sector, is an attempt to describe the quantitative and qualitative relationships between possible benefits and costs of undertaking new projects or replacing the old ones. Greater the BCR, more viable the project is [15].

Analysis of Fig 15, Fig **16**, Fig **17** & Fig **18** ,representing NPV, IRR, payback periods and BCR's of modelled FPSWH system application at selected locations of

Pakistan respectively, shows that all economic determinants favour the location having Lat.= 30.3^{o}N (Quetta city) the most with maximum NPV, IRR and BCR values and minimum payback period for the installation of modelled system. Following the Quetta city, Karachi (Lat. = 24.9^{o}N) and Gilgit (Lat. = 35.9^{o}N) show the same feasibility. Then Peshawar (Lat. = 34.0^{o}N) and Lahore (Lat. = 31.5^{o}N) stand in feasibility descending order. While the Islamabad capital (Lat. = 33.6^{o}N) is least feasible location for modelled FPSWH system application with minimum NPV, IRR and BCR values and maximum payback period.

Based on comparative analysis, economic determinants favour the selected cities for modelled FPSWH system application in following settling order; Quetta, Karachi ~ Gilgit, Peshawar, Lahore and least one Islamabad capital. Quetta city is the most feasible because of fact that useful heat energy (exergy) value delivered by solar flat plate collectors is highest than in other cities although solar irradiance value is not maximum in Quetta. The reason is; useful heat energy delivered by solar collector/s is not a function of solar irradiance. Solar irradiance value signs possible solar fraction of system [12] while useful heat energy delivered by solar collector/s is defined by absorbed solar radiations, collector/s losses, collector/s area, ambient temperature, wind speed and fluid inlet temperature [12]. On the other hand useful heat energy value delivered by solar collector/s in Islamabad capital is lowest among all, that's why the capital city is least feasible. Selected cities show same economic feasibility behaviour for modelled FPSWH system application as in useful energy delivered by collectors curve (shown in Fig 19).

Overall, all the selected cities are feasible for modelled FPSWH system application as all locations show positive NPV, having IRR value greater than discount rate [24]. Payback period values for all cases are even less than the half of projected 20 years project life. And BCR value is also greater than one [15] at all selected locations for modelled FPSWH system installation.

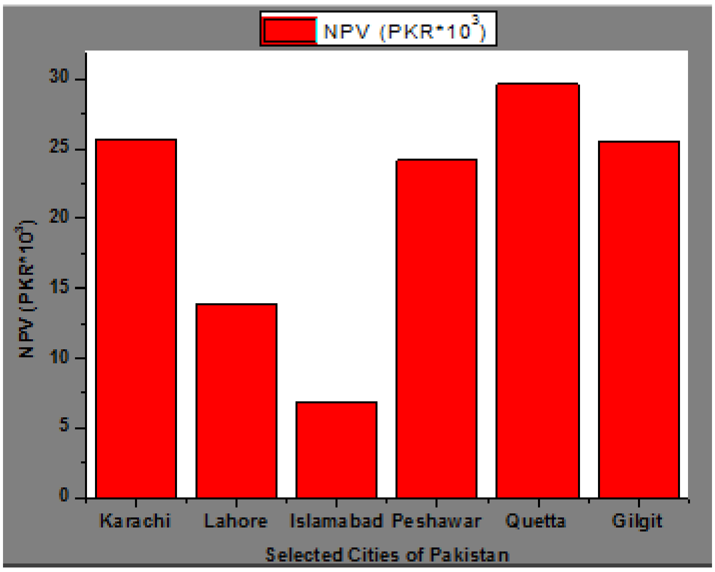

Fig 15: NPV based economic analysis

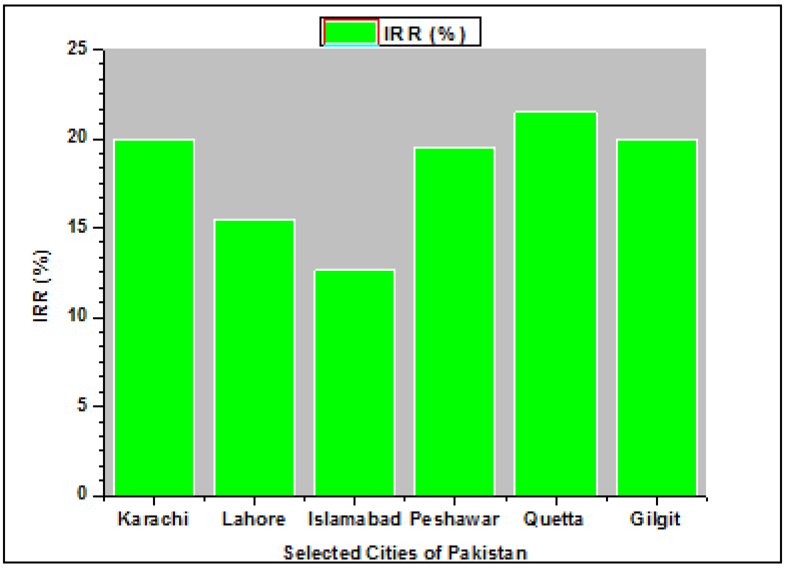

Fig 16: Economic evaluation in terms of IRR

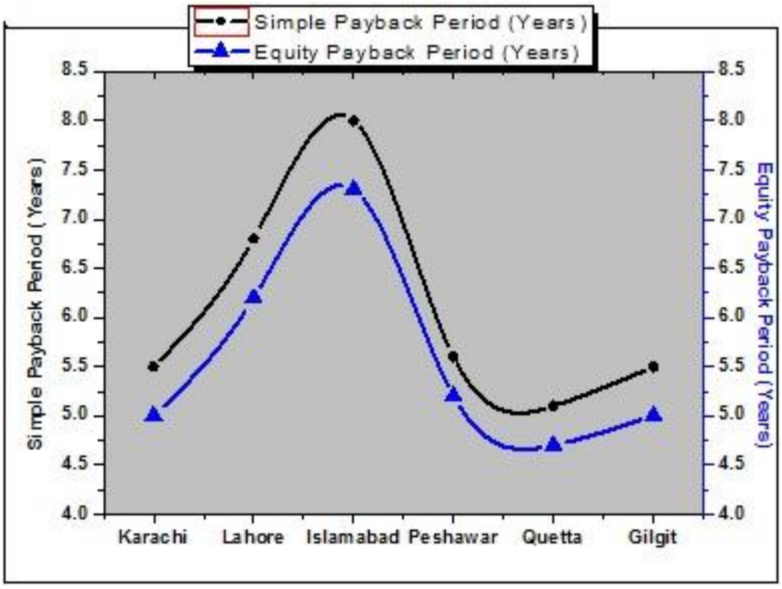

Fig 17: Equity & simple payback periods based economics

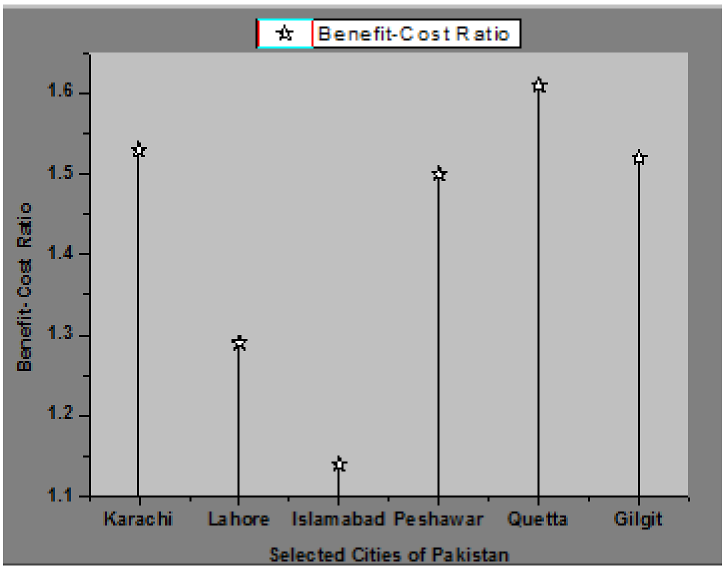

Fig 18: Benefit-cost ratio (BCR) of modelled FPSWH system

5.2 Technical Analysis

In technical analysis; solar fraction of FPSWH system, useful heat energy delivered, backup fuel (natural gas fuel) savings and consumption have been analysed and discussed.

Solar fraction of FPSWH collector/s largely depends upon solar radiations falling on collector/s surface. Greater the value of solar radiations falling on collector/s surface horizontally, larger the value of solar fraction would be [12]. Relationship between the percentage solar fraction and useful heat energy of FPSWH system is shown in

Fig 19. Analysis of Fig 19 shows that it is not necessary for a system with maximum solar fraction to have maximum corresponding system useful heat energy value too, because useful heat energy value doesn't depend on solar fraction of system but on factors like collector area, absorbed solar radiations of collector/s, collector/s overall losses, wind speed, ambient temperature and fluid inlet temperature [12]. That's why flat plate collector in Quetta climate delivers maximum useful heat energy against 71% solar fraction value that is less than of FPSWH systems modelled for Karachi and Peshawar regions. FPSWH system evaluated for Karachi region operates on maximum value of solar fraction but has 2nd maximum delivered useful heat energy value. Flat plate collector in Islamabad capital delivers minimum value of useful heat energy but solar fraction value of the system at this Lat. position is greater than FPSWH system working at Gilgit site. In short, Percentage solar fraction of FPSWH system is in following location based descending order; Karachi, Peshawar, Quetta, Lahore, Islamabad and Gilgit. While useful heat energy delivered flat plate collector for water heating is in following location based descending sequence; Quetta, Karachi ~ Gilgit, Peshawar, Lahore and Islamabad.

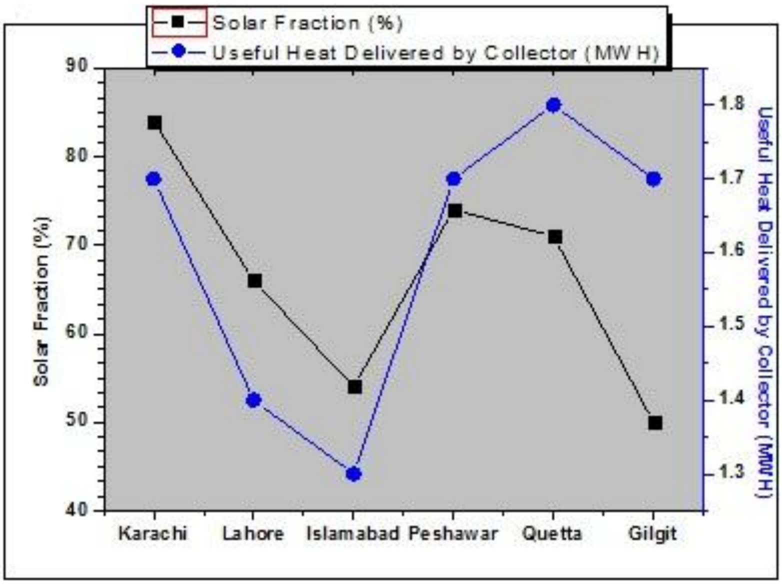

Fig 19: Percentage solar fraction of FPSWH collectors (%) and useful heat energy delivered (MWH)

Main aim of the world's trend towards renewable energy resources utilization is to reduce the dependence on fossil fuels that are near to be extinct. Natural gas is a major fuel being used in Pakistan for water heating purpose especially during winter season. Fig 20 shows the diminution in natural gas consumption because of a modelled FPSWH system installation in six major cities of Pakistan. Results show that about 50-85% reduction in natural gas fuel consumption could be achieved. Reduction in natural gas fuel consumption depends upon solar fraction of the system [11]. As analysis shows, 84.4% reduction in natural gas fuel consumption could be achieved in Karachi city where modelled FPSWH system operates with maximum solar fraction value, 74.41% reduction at Peshawar location, 71.03% reduction in Quetta territory, 65.85% reduction for Lahore region, 53.5% reduction in Islamabad capital and 50% reduction in natural gas fuel consumption at Gilgit heights are possible to be achieved where modelled FPSWH system operates with minimum solar fraction value.

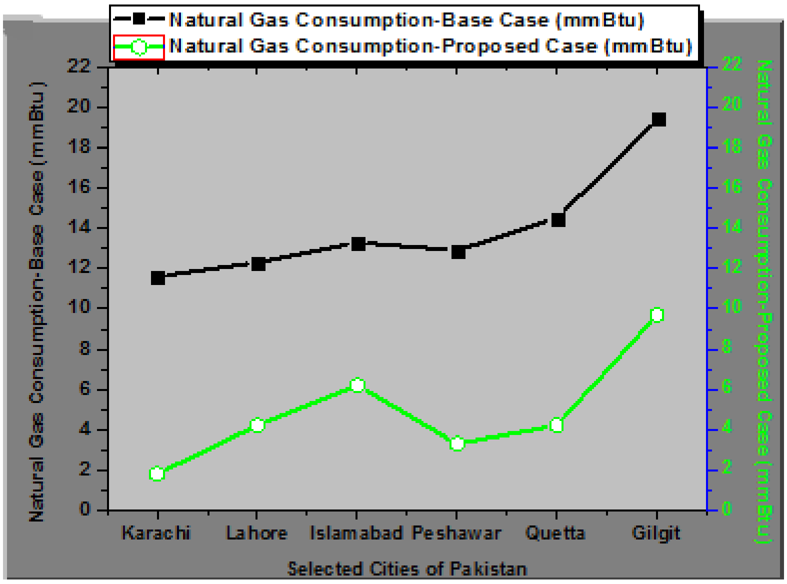

Fig 20: Natural gas fuel (backup fuel) consumption and savings

5.3 Environmental Analysis

GHG emissions worried the whole world a lot. It remained the most concerned issue during the last decade particularly, that's why many protocols and standards have been set to control the emissions. FPSWH system application points towards reduced fossil fuels combustion that ultimately results in GHG emissions reduction. As Fig 21 interprets GHG emissions reduction that could be achieved by installing modelled FPSWH system. Analysis predicts that 0.6tCO_2 emissions could be reduced by installing single modelled FPSWH system in Quetta/Karachi. 0.5tCO_2 GHG emissions reduction is possible in Peshawar, Lahore or Gilgit each and 0.4tCO_2 GHG emissions could be reduced through single modelled FPSWH system installation in Islamabad capital.

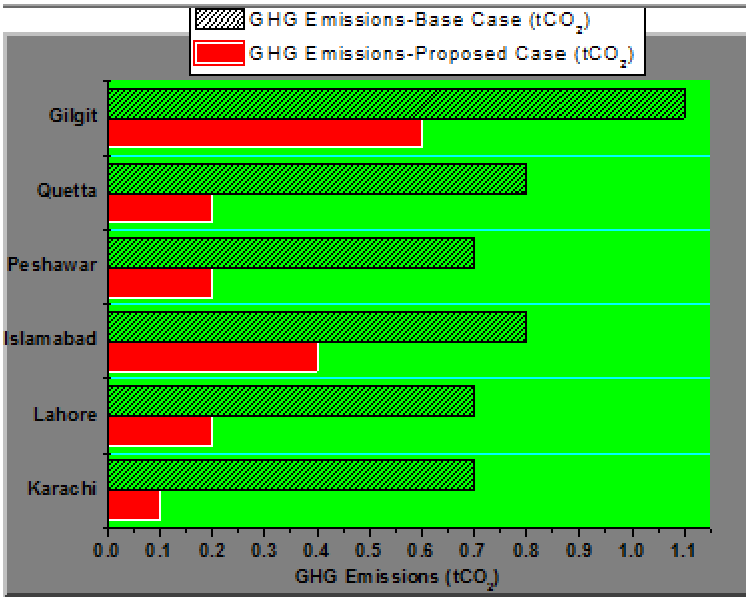

Fig 21: GHG emissions reduction possible through a FPSWH system installation

Conclusions

FPSWH system is modelled in RETScreen software using certain standards and input parameters. Techno-economic viability of modelled FPSWH system is evaluated on the basis of project economical, technical and environmental parameters for six major cities (representing five provinces and federal capital) of Pakistan. After analysing the results, it is concluded that:

- Techno-economic viability of FPSWH system is the function of useful heat energy delivered by solar collector/s of the system.
- Location having Lat. = 30.3°N (Quetta city-capital of Balochistan) is the most feasible site for modelled FPSWH system application favoured by all examining parameters, while location having Lat. = 33.6°N (Islamabad city-federal capital) is least feasible.
- In-between the most and least feasible sites, locations with Lat. = 24.9°N (Karachi city-capital of Sindh province) and Lat. = 35.9°N (Gilgit city-capital of Gilgit Baltistan province) show almost same viability after Quetta; followed by a location having Lat. = 34.0°N (Peshawar city-capital of Khyber Pukhtoon kha province). Then location with Lat. = 31.5°N (Lahore city-Capital of Punjab province) shows feasibility as predecessor of the least feasible Islamabad capital.
- It is found that the installation of modelled FPSWH system, working on 50-80% accumulative system solar fraction, would lead to reduction in the natural gas

fuel consumption by 35% to 75% per home that would result in reduced GHG emissions up to 0.4-0.6 tCO_2 per home.

- Also it is observed that the payback period of the FPSWH system for different selected locations of Pakistan varies between 4.5 to 6.5 years based on the savings achieved due to reduced consumption of natural gas fuel (backup fuel).

SWH technology is the need of time in energy's future concerns especially for countries which are already facing disastrous situation of energy sector, like Pakistan. It will not only help in reducing natural gas fuel consumption (where gas fuel is used for water heating purposes) but also be helpful in overcoming natural gas fuel shortage especially during winter season and in green growth of Pakistan.

NOMENCLATURE

CF	Cash flow
A_C	Collector area
A_P	Aperture area
t	Number of Periods
Q_U	Rate of energy gain
r	Rate of return per period
I_T	Hourly incident radiation
L	Monthly total Heating load
FrU_L	Co-efficient of thermal losses
Fr	Collector heat removal factor
N	Number of days in the month/s
$Fr(\tau\alpha)$	Co-efficient of optical efficiency
$\tau\alpha$	Transmittance- absorptance product
T_{ref}	Empirical reference temperature ~ 100^{o}C
T_a	Monthly average ambient temperature (^{0}C)
H_T	Average daily radiation incident on collector area
T_i	Temperature of fluid entering the collector inlet (^{0}C)

ABBREVIATIONS

Lat.	Latitude
GHG	Greenhouse gas
NPV	Net present value
BCR	Benefit-Cost Ratio
IRR	Internal rate of return
BTU	British Thermal Units
FPSWH	Flat Plate Solar water heater/heating
NASA	National Aeronautics and Space Administration
OECD	Organization for Economic Co-operation and Development

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