Energy Analysis of Roof Integrated Solar Collector for Domestic Heating & Cooling Under Local Conditions of Pakistan

Muhammad Imran*[‡], Hameed Ullah Mughal**

*Faculty of Engineering, University of Central Punjab Lahore

**Department of Mechanical Engineering, University of Engineering & Technology Lahore

imrangilani@ucp.edu.pk, pdhumughal@uet.edu.pk

[‡] Corresponding Author; Muhammad Imran, Faculty of Engineering, University of Central Punjab Lahore, Pakistan, +92-42-35880007, imrangilani@ucp.edu.pk

Received: 09.10.2012 Accepted: 10.01.2013

Abstract- Household utilization of energy represents the 46% of Pakistan total energy. This situation requires that new energy model & alternates of energy should be developed for the household utilization of energy. Solar Energy is one of the best available options for this problem. Many designs of solar roof have been developed in the last half century to utilize solar energy from the roof. The previous designs are feasible but their design is complex and their performance. A model of Roof Integrated Solar collector is designed & fabricated. The dimensions of collector are 5 feet long, 4 feet wide & 0.5 feet height. Experimental readings are taken at various times of the day. The effect of orientation is also studied experimentally. Economic analysis is performed for different scheme of solar collector using linear economical approach. Energy Analysis shows that Roof Integrated Solar collector has a very healthy potential for solar thermal application as it has almost 37 % efficiency. The major loss occurs in solar collector. The life cost analysis shows that the cost of Roof Integrated Solar collector is very economical as compared to electric water heater, gas water heater or solar thermal water heater. Energy distribution analysis shows that 37% energy is transferred to water, 32 % is reflected back & 22 % is transferred to the atmosphere through collector walls & base & the rest of 9% is absorbed by the collector surface.

Keywords- Roof Integrated Solar Collector, Energy Analysis, Solar Energy, Economic Assessment.

1. Introduction

A research conducted by the Pakistan Council for Renewable Energy Technologies (PCRET) shows that household utilization of energy represents the 46% of Pakistan total energy. This value is expected to increase by 16% at the end of 2012 [16]. This situation requires that new energy model & alternates of energy should be developed for the household utilization of energy. Solar Energy is one of the best available options for this problem. It will not only decrease the residential energy demand but also it will contributes towards safe environment as it is pollution free energy source. The energy demand in residential sector suddenly rises in summer where space cooling consume major portion of energy. Space cooling with solar energy can play vital rule in this case, as Pakistan is the 6th luckiest country which have almost 300 sunshine days in a year & an average 2500 sunshine hours in a year.

Many designs of solar roof have been developed in the last half century to utilize solar energy from the roof. The previous designs are feasible but their design is complex and their performance & efficiency is low as compared to cost of fabrication. Previous research shows that solar electric systems are expensive than solar thermal. The capital cost & running cost of solar electric system is higher as compared to solar thermal. So there is enough space for the research in solar thermal systems for heating & cooling.

2. Roof Integrated Solar Collector

The roof integrated solar collector utilizes the natural roof designed coupled with a very simple double glass collector which makes it very economical. An insulated layer is used to cover roof and side walls of the roof to provide thermal insulation to hot water. The insulated roof and side walls provides a water tight chamber.

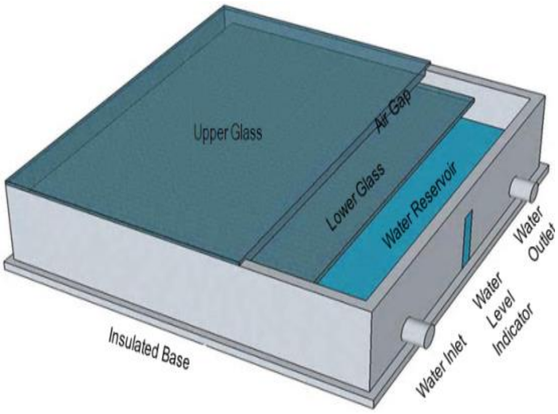

Fig. 1. Roof Integrated Solar Collector

Two glass layers are placed on the side walls of roof with 2 cm above the water level and almost 1 cm distance between the two glass layers. An inlet and outlet for water is available at the front side wall of roof and a transparent water level indicator. A medium size pump will be used to circulate the hot water through the system. It is a fixed mass solar water heater. A simple design of intended roof integrated solar collector is shown in Figure 1.

3. Literature Review

Ming Qu et al. [1] performed Energy & Exergy analysis of a solar thermal cooling system at Carnegie Mellon University with respect to its design, installation & modelling. He suggested that orientation of solar collector have strong impact on the performance of solar cooling and heating system. The most feasible orientation is NS for cooling and EW for heating. Storage tank, drain-back tank & diameter of the supply pipe determine the optimum performance of solar collector. Frank Kreith et al. [2] suggested preliminary design of solar cooling systems. A linear model is presented for the calculation of energy of a solar cooling and heating systems for residential buildings. Result shows that the design of solar collector is important since major loses occurs within solar collector. Life Cycle Cost & Internal Rate of return is also calculated for cooling & heating system. Lamp and Ziegler [3] pointed out that wintertime heating is also taken into account. The payback period is reduced by 1.5 years with an increase in capital investment. Marco Beccali et al. [4] presented a comprehensive energy analysis & economic performance evaluation of a desiccant cooling system.

The desiccant cooling system is compared under various conditions. Result shows that many desiccant cooling systems have very good performance in humid and hot climate with high temperature of heater in desiccant cooling system. H. Zhai et al. [5] investigated energy analysis of a hybrid solar heating, solar cooling and solar thermal power generation system for remote areas. Result shows that maximum energy loss occurs in solar collector for each heating, cooling & power generation. The system energy and exergy was almost 57.0% and 14.2%, respectively. Comparison of energy and exergy analysis of these systems shows that they have higher efficiency as compared to thermal power systems with Rankine cycle. C. Onan et al. [6] performed Exergy analysis of a solar absorption cooling system for residential buildings under different temperatures & outdoor conditions. The calculations are performed under transient conditions for energy and exergy & it is observed that the major energy losses occur in the solar collectors and generator. Exergy loss in the collector varies from 20% to 75% while exergy loss in the generator varies from7% to 9%. X.Q. Zhai et al. [7] presented experimental investigation and performance evaluation of a solar adsorption cooling system under heat storage and solar adsorption cooling system without heat storage. Results indicate that solar adsorption cooling system with heat has higher solar collecting efficiency as compared to solar adsorption cooling system without heat storage. The system without heat storage has high energy saving potential due to higher Coefficient of Performance. C. Sanjuan et al. [8] investigated system with interior energy storage & optimize its performance using dynamic simulation model. The model includes the field of solar collector, the absorption heat pump and the building cooling & heating load calculations. Simulation was carried out for different system configurations & optimization of solar collector & heat pump is suggested. F. Calise et al. [10] presented a transient simulation model for solar heating and cooling system in three different configurations to evaluate technical and economic feasibility of the system. Result shows that economical solar heating & heating will utilize the best suitable flow rate of pump as well as the volume of storage tank.

S. Medved et al. [12] presented the design methodology, economic and energy analysis for the calculation of the efficiency of a large panel unglazed roof integrated liquid solar collector for a swimming pool. Different factors that affect the performance of collector are considered and discussed. These factors include length f fin; material of the absorber and its thickness; mass flow rate of water and the wind speed. Results shows that efficiency varies from 0.29 to 0.78 and the heat loss factors are in the range of 2.7-7.5 under no wind condition. Economic analysis shows that the payback period is between 1.6 and 2.8 years. Literature review shows that no research has been conducted on the energy & economic analysis of roof integrated water solar collector for domestic heating & cooling for Pakistan. For the aim to show the feasibility and advantages of the newly developed roof-integrated, water solar collector on the perspective of energy as well as thermal comfort & economic feasibility. Based on the energy simulation results, the energy characteristics of the roof-integrated water solar collector will be investigated. Solar energy available is calculated using mathematical models and the result is compared with actual data available from Pakistan Meteorology Department. The solar potential of Lahore is also compared with different cities of the world which shows that Lahore has much more solar potential than those cities. Solar collector is designed and fabricated. Energy analysis is performed and performance and efficiency is calculated with different glazing materials and with different orientation. A suitable cooling method is suggested based upon the output of collector. Life Cycle Cost tool is used to evaluate the economic feasibility of the solar collector. The results are compared with that conventional water heating system.

4. Solar Potential of Lahore

The geographic position and climatic conditions of Pakistan make it ideal for feasible & economical utilization of solar energy.

It has more than 300 sunshine days in a year with almost 2500 sunshine hours. The irradiation data for six major locations of Pakistan is shown in Table 1 [13].

Table 1. Monthly average daily irradiation values at different locations in Pakistan MJ/m2 per day

Month	Karachi	Lahore	Islamabad
Jan	15.3	10.5	10.1
Feb	20.2	17.6	15.5
Mar	20.2	17.6	15.5
Apr	22.2	21.6	22.0
May	23.0	23.1	24.3
Jun	22.5	23.6	23.3
Jul	17.5	18.9	21.1
Aug	16.8	19.5	20.5
Sep	30.1	19.8	19.5
Oct	18.9	19.8	15.7
Nov	15.7	12.4	11.6
Dec	14.1	10.2	8.1

5. Solar Energy Calculation for Lahore

Calculation of available solar energy at a site is a basic tool for the sizing of any solar energy system. Solar energy varies with geographical location and season. For a specific location and season a definite amount of energy will be available in a day of clear sky. Different solar-earth geometrical parameters (Equation of time, declination, azimuth angle & zenith angle etc.) are used for calculation of solar energy. These parameters are calculated for 14th May 2011 for the city of Lahore (Latitude = 31.51 Degree North, Longitude =74.4 Degree East). The time Zone of Pakistan from Greenwich is +5 hour. Solar energy will be estimated for 14th of May 2011. For 14th may the corresponding day number (n) is 134. The solar energy parameters are shown in table 2.

Table 2. Solar Energy Parameters

No.	Parameter	Values
1	Equation of Time (E)	3.86 Mint
2	Declination Angle (δ)	17.87 Deg.
3	Solar Hour (h)	30 Deg.
4	Solar Altitude (α)	59.95 Deg.
5	Azimuth Angle (A)	109.594 Deg.
6	Zenith Angle (θz)	30.34 Deg.

6. Monthly-Averaged Daily Horizontal Global Irradiation

A general expression for calculation of Monthly-averaged daily horizontal global irradiation is given by

$$G = E\left[a - b\left(n/_N\right)\right]$$

$$E = (0.024/\pi) I_{SC}\left[1 + 0.033\cos(360DN/365)\right]\left[\cos\emptyset\cos\delta\sin W_S + (2\pi W_S/360)\sin\delta\sin\emptyset\right]$$

$$N = \left({2W_S}/_{15}\right)$$

$$W_S = \cos(-\tan\emptyset\tan\delta)$$

For Lahore

a = 0.326 & b = 0.314

E (KWh/m^2) = 11.0943

7. Monthly-Averaged Daily Horizontal Diffuse Irradiation

A general expression for calculation of Monthly-averaged daily horizontal diffuse irradiation is given by

$$D/_G = 1.35 - 1.61K_T$$

K_T = Constant (For Lahore K_T = 0.65)

D = 3.36712 kWh/m^2

8. Energy Available at Horizontal Roof

The daily energy which (Ed) which is available at the horizontal roof can be calculated by the equation given by

$$E_D = G^{\circ}\cos\theta\,\epsilon\,A/30$$

To find the Angle of incident, using the relation

$$\cos\theta = (A - B)\sin\delta + [C\sin w + (D + E)\cos w]\cos\delta$$

Where all these parameters are calculated & presented in table 3

Table 3. Daily energy (Ed) Solar Energy Parameters

Sr. No.	Parameter	Value
1	A= sin δ sin β	0.00
2	B = Cos Φ Sin β Cos γ	0.00
3	C = Sin β Sin γ	0.00
4	D = Cos Φ Cos β	0.85
5	E = Sin Φ Sin β Cos γ	0.00

So we get, θ = 35.76 Degree & daily energy (E_D) available at the horizontal roof is given by

E_D = 13820.78672 Wh = 49754832.192 Joul

E_D = 49.754832192 MJ

9. Energy Demand & supply for Water Heating

The amount of heat absorbed by the water is given by the equation

Inlet Water Temperature = 25° C
Out let Water Temperature = 40° C
Width of solar collector = 9.85 feet = 3 m & Length of solar collector = 12.5 feet = 3.8 m
Depth of solar collector = 0.5 inch = 0.0254 m
Volume = 3 x 3.8 x 0.0254 = 0.293526 m3
Mass = density x volume
Density of Water = 1000 Kg / m^3
Mass of Water = 1000 X 0.293526 = 293.526 Kg
Q = m C Δ T = 293.526 x 4.18 x 15 = 18404 KJ
Q = 18.404 MJ

10. Efficiency of Roof Integrated Solar Collector

Efficiency of the roof integrated solar collector is given by the relation

η = Output (Heat of Hot Water) / Daily energy collected (Ed) for the horizontal roof
η = 18.404802/49.754832192
η = 37 %

10.1. Snell's Las

The ratio of angle of incident to angle of refraction is equal to ratio of refractive index of their mediums. As shown in equation below

$$n_1 \text{Sin}\theta_1 = n_2 \text{Sin}\theta_2$$

Refractive index of air = n1 = 1.0008 & Refractive index of glass = n2 = 1.510

Angle on incident = θ i = 35.6 Degree

Angle of transmission = θt= 22.788 Degree

10.2. Fresnel's Equations

The transmission and refraction of electromagnetic waves is completely described by the Fresnel's equations. Fresnel's equations are used to calculate the refraction and transmission coefficients in terms of angle of incident and angle of refraction.

10.3. Reflection Coefficients

$$r_{||} = \frac{\tan(\theta i - \theta t)}{\tan(\theta i + \theta t)}$$

= 0 .1408942319589772

$$r_{\perp} = \frac{Sin\ (\theta i - \theta t)}{Sin\ (\theta i + \theta t)}$$

= - 0.26313361896873954

10.4. Transmission Coefficients

$$t_{||} = \frac{2sin\theta tCos\theta i}{Sin(\theta i + \theta t)\ Cos\ (\theta i - \theta t)}$$

= 0.7561635412877777

$$t_{\perp} = \frac{2sin\theta tCos\theta i}{Sin(\theta i + \theta t)}$$

= 0.7368663810312606

Checking out conservation of energy in this situation leads to the relationship. This applies to both the parallel and perpendicular case

$$r^2 + t^2 \frac{n_2\ Cos\theta t}{n_1 Cos\theta i} = 1$$

11. Performance Evaluation of Collectorat Different Time of the Day

Temperature of the water at outlet is measured at different time of the day and also at different orientation of the collector. The variation of water temperature for different orientation is measured and compared which suggest that collector at an angle 15 degree with horizontal is most feasible orientation of collector which gives the maximum temperature of water. The table 4 shows the variation of temperature of water when it is in horizontal position, i.e. in normal condition.

Table 4. Temperature Variation of water for horizontal roof Integrated Solar Heater

No	Time	Duration (Hour)	Temperature (°C)
1	09:00	0	25
2	10:00	1	26
3	11:00	2	27.5
4	12:00	3	30.5
5	13:00	4	33.5
6	14:00	5	36.5
7	15:00	6	38
8	16:00	7	39.5
9	17:00	8	40
10	18:00	9	40.5

11.1. Performance Evaluation of Open Water Heating

To compare the result of roof integrated solar collector with the simple open air water heating directly exposed to sunlight, different readings of temperature are taken for open water heating system as shown in table 5.

11.2. Performance Evaluation of Collector at different Orientations

Previous research shows that the best performance of solar collector is at inclination with horizontal. The roof integrated solar collector is tilted at an angle of 15 degree and the temperature variation is recorded, variation trend is shown in table 6. It shows that it has better performance than horizontal orientation. But the incline orientation will increase the price of the solar collector and hence it has to be compromised between the solar collector performance and cost.

Table 5. Temperature Variation of water for open air water heating by Solar Energy

No	Time	Duration (Hour)	Temperature (C)
1	09:00	0	25
2	10:00	1	25
3	11:00	2	25.5
4	12:00	3	26
5	13:00	4	26.5
6	14:00	5	28
7	15:00	6	28.5
8	16:00	7	29
9	17:00	8	29
10	18:00	9	29

Table 6. Temperature Variation of water for tilt roof Integrated Solar Heater

No	Time	Duration (Hour)	Temperature (C)
1	09:00	0	25
2	10:00	1	26
3	11:00	2	28
4	12:00	3	31
5	13:00	4	34
6	14:00	5	36
7	15:00	6	39
8	16:00	7	41.5
9	17:00	8	42
10	18:00	9	42.5

The graphical representation of variation of orientation of roof Integrated Solar Heater with respect to temperature is shown in Figure 2, Figure 3 & Figure 4.

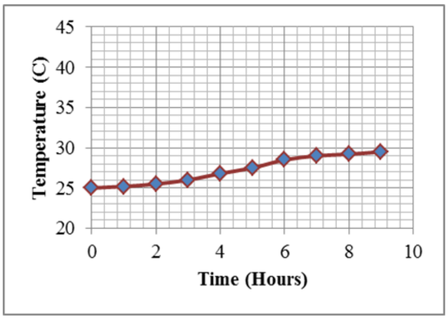

Fig. 2. Temperature Variation of water for Open Surface Water Heating

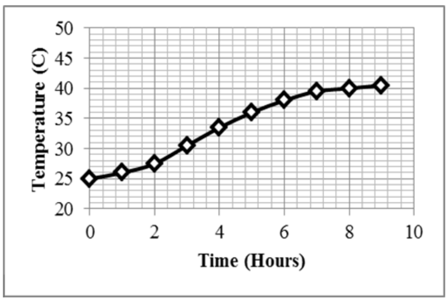

Fig. 2. Temperature Variation of water for Horizontal roof Integrated Solar Heater

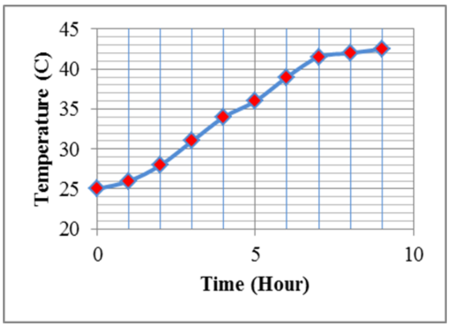

Fig. 3. Temperature Variation of water for tilt roof Integrated Solar Heater

12. Conclusion

- Energy Analysis shows that Roof Integrated Solar collector has a very healthy potential for solar thermal application as it has almost 37 % efficiency. The major loss occurs in solar collector.
- Energy analysis shows that the orientation of collector has strong relationship with the water temperature. The most suitable orientation is to use the collector at an inclination (10-30) with horizontal. Roof Integrated Solar Water orientation at 15 Degree gave the best performance. The results at different orientation are shown in figure 5.
- Air is used between the glass layers to prevent the heat transfer of hot water from the water reservoir. Since thermal conductivity of air is low so the thickness of air gap affects the performance of the collector. There is a compromise between the air gap thickness and the heat transfer. Previous research shows that the optimum air gap should be around 1cm to avoid air transfer from water reservoir.
- As compared to the design of previous solar water heater the design of roof integrated solar collector is very simple. There are only two main components the insulated water reservoir and two gas layers separated with 1 cm air gap.
- The glass thickness also affects the temperature of water since thermal conduction is directly related to the thickness. 5mm & 3mm glass are used the results of 3mm glass are better than the 5mm. But low thickness of glass leads to the fragility.
- Energy distribution analysis shows that 37% energy is transferred to water, 32 % is reflected back & 22 % is transferred to the atmosphere through collector walls & base & the rest of 9% is absorbed by the collector surface.
- Energy Available at collector surface is almost 49.75483219 MJ, since 98 % is transmitted so energy entering in air gap is given by 49.75483219 - 0.2 x 49.75483219 = 39.803865752 MJ, if we consider the walls of collector perfectly insulated then again 98% energy is transmitted through second glass which is given by 39.803865752- 0.2 x 39.803865752 = 29.8528993 MJ, this the energy available to heat the water should be 29.8528993 but experimental readings shows that the available energy in water is 18.40893 MJ so rest amount of energy i.e. 29.8528993 - 18.40893 = 11.4439693 MJ is heat loss

through the collector walls and base. Energy Distribution of Solar Collector is shown in figure 6.

- In winter hot water from the collector will be is used for household and space heating but the higher demand of energy is in summer where space cooling is necessary, most economical method is to utilize the hot water from collector with auxiliary gas heater for desiccant cooling. The temperature range for desiccant cooling is 70-90 Degree Centigrade. Experiment shows that almost 40-50% heat should be supplied from the backup system either gas or electric heater coupled with roof integrated solar collector.
- There is enough space for further research in the thermal design of collector, as the amount of reflected energy and energy transferred from the water reservoir is higher enough which can be improved by using the proper insulated material as well as the suitable glazing material.

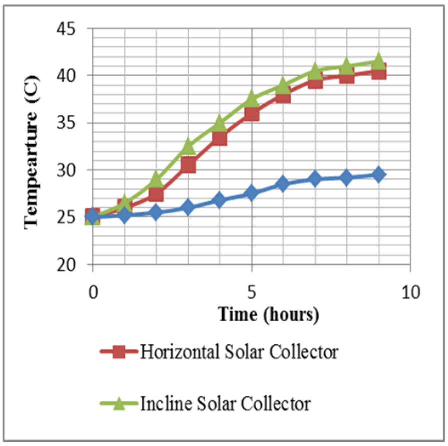

Fig. 4. Comparison of various Collector orientations

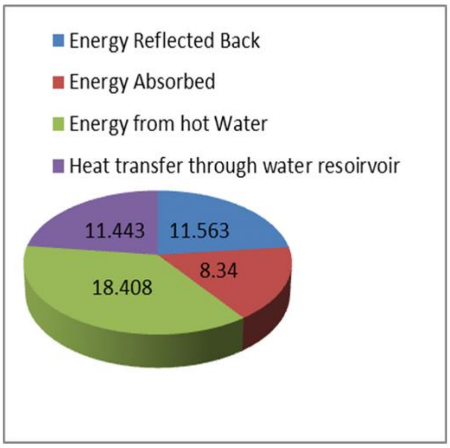

Fig. 5. Energy Distribution of Solar Collector

References

[1] Ming Qu, Hongxi Yin, David H. Archer. A solar thermal cooling and heating system for a building: Experimental and model based performance analysis and design. Solar Energy, Volume 84, Issue 2, February 2010, Pages 166-182

[2] Frank Kreith, Jan F. Kreider- Preliminary design and economic analysis of solar-energy systems for heating and cooling of buildings, Energy, Volume 1, Issue 1, March 1976.

[3] P. Lamp, F. Ziegler European research on solar-assisted air conditioning International Journal of Refrigeration, Volume 21, Issue 2, March 1998, Pages 89-99

[4] Marco Beccali, Pietro Finocchiaro, Bettina Nocke. Energy and economic assessment of desiccant cooling systems coupled with single glazed air and hybrid PV/thermal solar collectors for applications in hot and humid climate. Solar Energy, Volume 83, Issue 10, October 2009, Pages 1828-1846

[5] H. Zhai, Y.J. Dai, J.Y. Wu, R.Z. Wang. Energy and exergy analyses on a novel hybrid solar heating, cooling and power generation system for remote areas. Applied Energy, Volume 86, Issue 9, September 2009, Pages 1395-1404

[6] C. Onan, D.B. Ozkan, S. Erdem. Exergy analysis of a solar assisted absorption cooling system on an hourly basis in villa applications. Energy, Volume 35, Issue 12, December 2010, Pages 5277-5285

[7] X.Q. Zhai, R.Z. Wang. Experimental investigation and performance analysis on a solar adsorption cooling system with/without heat storage. Applied Energy, Volume 87, Issue 3, March 2010, Pages 824-835

[8] C. Sanjuan, S. Soutullo, M.R. Heras. Optimization of a solar cooling system with interior energy storage. Solar Energy, Volume 84, Issue 7, July 2010, Pages 1244-1254

[9] Umberto Desideri, Stefania Proietti, Paolo Sdringola. Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. Applied Energy, Volume 86, Issue 9, September 2009, Pages 1376-1386

[10] F. Calise, M. Dentice dAccadia, A. Palombo. Transient analysis and energy optimization of solar heating and cooling systems in various configurations. Solar Energy, Volume 84, Issue 3, March 2010, Pages 432-449

[11] Rangsit Sarachitti, Chaicharn Chotetanorm, Charoenporn Lertsatitthanakorn, Montana Rungsiyopas. Thermal performance analysis and economic evaluation of roof-integrated solar concrete collector. Energy and Buildings, Volume 43, Issue 6, June 2011, Pages 1403-1408

[12] Medved, C. Arkar, B. erne. --A large-panel unglazed roof-integrated liquid solar collectorenergy and economic evaluation. Solar Energy, Volume 75, Issue 6, December 2003, Pages 455-467

[13] A. Khalid, M. Mahmood, M. Asif, T. Muneer. Solar assisted, pre-cooled hybrid desiccant cooling system for Pakistan. Renewable Energy, Volume 34, Issue 1, January 2009, Pages 151-157

[14] Pakistan Meteorology Department Headquarter Office Sector H-8/2 Islamabad, Website: http://www.pakmet.com.pk