Chapter

Energetics and GHG Emission Mitigation Potential Estimation of Solar Water Heating System in India

Bhupendra Singh Rawat, Pradeep Chandra Pant, Poonam Negi and Bharti Ramola

Abstract

The aim of this study is focused on "energetics" or energy analysis and evaluation of greenhouse gas (GHG) mitigation potential of solar water heating system (SWHS) having 100 litre per day (lpd) capacity in 28 states of India. Different types of collectors are used in solar water heating system, which may affect on the feasibility of the system. So to analyze this factor, the present approach focused on three types of glazed flat plate collectors. In addition to this, the feasibility of the system also does depend upon the end user applications. So to incorporate more feasible analysis, three different scenarios were considered. For the analysis of environmental impact of the system, GHG emission mitigation potential has also been evaluated by assuming the replacement of the system with frequently used fuels, viz., natural gas, coal, diesel, etc. This was done for both seasonal and annual use of this renewable energy thermal device. The result of this study shows that energy payback period (EPBP) and energy yield ratio (EYR) values for selected locations are in the adoption level. In case of coal, the GHG-emission reduction was found to have a maximum value of 22.4 tCO_2 for the state of Rajasthan and a minimum value of 13.4 tCO_2, for Jammu & Kashmir, for 20 years of useful lifetime of the system.

Keywords: energy analysis, energy payback period, energy yield ratio, glazed flat plate collectors, GHG emission mitigation

1. Introduction

Energy security is a goal that many countries are pursuing to ensure that their economies function without interruption and that their peoples have access to adequate, reliable and affordable supplies of modern and clean energy. It is a pressing concern because the demand for energy is growing rapidly due to robust economic expansion, population growth, new uses of energy and income growth and yet the supplies of energy resources required to power these needs are finite and in most cases nonrenewable. Furthermore, the production, transportation and utilization of energy are a major source of greenhouse gases that cause global warming and climate change. In this perspective energy management may play vital role in the optimization of any renewable energy system via energy analysis or by means of some other methods. Further, renewable energy systems have been proven to have potential in the reduction of greenhouse gas emission [1–7].

The application of solar energy utilization in the form of thermal energy is for heating water for domestic, commercial and industrial uses and range from the temperature 80–240°C [8–10]. During the last two decades with the emerging technologies and increasing demand the potential use of solar water heating system has been widely expanded, particularly in the residential sector [11]. The estimated gross potential for solar water heating systems in residential sector of India is quite massive [12]. In a typical Indian house, the energy consumed for heating water for bathing purpose ranges from 2000 to 7000 GJ/annum depending upon the location/weather conditions. In industries also, hot water requirement is quite high and therefore the energy consumption is many times higher than the above value. This energy requirement is being fulfilled by grid extension, coal, furnace oil, LPG/natural gas, wood, etc. For development, dissemination and the promotion of solar water heating system in different sectors, significant efforts have been made by the government of India. Solar water heating system of 5.6 GWth, capacity was proposed to be added in the duration of 2012–2017 and achieve 14 GWth by 2022 [13]. For the promotion and dissemination of solar water heating system like other renewable energy systems among people, government of India has been implemented several programs. This includes the dissemination of the projects, financial support or subsidies, awareness programs and through research and development [14].

A significant energy input is expected in the installation of solar water heating systems worldwide. *Energy analysis* of solar water heating system for domestic or commercial applications, gives information about the embodied energy in its various components and their share during installation and its useful lifetime. The significance of energy analysis lies in the fact that present day energy requirements are being met mainly from non-renewable energy sources, which are available as finite stores and are bound to be exhausted. Webb and Pearce [15] attribute the genesis of energetic to the awareness that these sources need to be judiciously utilized. Identification of energy-intensive components and their replacement with lesser once is the main advantage of energy analysis. This minimizes the overall energy demand of the system and gives a chance of utilization or implementation of this energy. In addition to this, energy analysis of the system and its comparison with the systems of similar technology may reduce the energy demand in any particular selected area. Energy analysis may provide useful approach for evaluation of energy yield ratio (EYR), energy payback period (EPBP) and GHG-emission mitigation potential of solar water heating systems for selected locations. This may also provide a comparative analysis of systems by different manufacturers and installation making decision for any selected location [16].

The design and efficiency of solar water heating system or any renewable energy system does depend upon the end user applications and climatic conditions of that particular location. Though the output energy of solar water heating system does depends upon the type of solar collector used, its efficiency, overall top loss heat transfer coefficient, number of glass covers used, available solar intensity, wind velocity of the location of installation [17–34].

There are several methods and simulation-based tools available for the design and energy analysis purpose. RETScreen, TRNSYS and SOLCHIPS, etc., are some user friendly tools, with the help of these tools, by the execution of number of simulation; one may analyze the effect of the variation of different variables on energy output given by the system. RETScreen software which is used in present study is also helpful for the evaluation of greenhouse gas emission mitigation potential of any renewable energy system in any particular location [35–38]. In addition to these tools, linear and nonlinear optimization techniques and evolutionary search algorithms have also been reported by different researchers to design the solar water heating systems [39–48].

Significant works have been carried out by different researches worldwide for the energy analysis and for the estimation of greenhouse gas emission mitigation potential of solar water heating systems having different collector area [49–55]. A comparative energy analysis study for the evaluation of energy payback period of solar water heating system having 3.6 m^2 of collector area with electric heater and gas water heater has been carried out by Crawford and Treloar [56]. A detailed life cycle analysis of solar water thermosyphonic system having collector area 2.13 m^2 was carried by Ardente et al. [57], where the estimated energy payback period was less than 2 years. An estimated energy payback period in between 5 and 19 months was found by Battisti and Corrado [58] after a detailed life cycle analysis for a thermosyphonic system having a 1.7 m^2 flat plate collector. They evaluated energy payback period on the basis of energy substituted with an estimated yearly output of 1958 MJ of the system. Asif et al. [59] compared the life cycle performance of two laboratory prototypes solar collectors made of Aluminum and Stainless Steel with built-in storage. They considered the collector area of 1 m^2 and found energy payback period in between 6 and 7 months for different locations on the basis of estimated energy output of the systems. Kalogirou [60] made an analysis for pressurized and thermosyphonic system having collector area of 3.8 m^2. The estimated value was found to be 1.2 years for the pumped system and 1.1 years for the thermosyphonic system. A fairly comprehensive comparative study of solar water heating system with three systems, based on conventional fuels was also carried out by Kalogirou [61]. In India, the evaluation of energy payback period of solar water heating system for different low altitude locations on the basis of energy analysis has been carried out by Mathur and Bansal [62]. Cumulated energy demand for the systems of different technologies was estimated by Mathur and Bansal [16]. They compared the solar water heating system with electric water heating system on the basis of energy analysis. Comparative study of solar water heater heating system of capacity 100 lpd with electric water heating system by using energy analysis method has been reported by Marimuthu et al. [63]. However, the estimation of energy consumption of the electrical water heater system was for the average temperature of Chennai. They also estimated the environmental benefits of the system on the basis of life cycle assessment of the system.

In the present study, "energetics" or energy analysis exercise has been undertaken on a domestic solar water heating system of 100 lpd capacity. Energy embodied in such systems have been estimated for three most prominent combinations of materials viz. Copper-Copper (Cu-Cu), Copper-Steel (Cu-Steel) and Copper- Aluminum (Cu-Al) were used in manufacturing the flat plate absorber of the flat plate solar collector, the main component of the solar water heating system. Three scenarios viz. optimistic, most probable and pessimistic were considered for the estimation of energy requirement in each and every component of the system during its useful lifetime of 20 years. Estimation of energy output by the system for one representative city of the 28 states has been considered. The lifecycle energy output and GHG-emission mitigation by the replacement of the solar water heating system with frequently used fuels viz. natural gas, coal, diesel, etc., have been estimated.

2. Methodology

In the present study, solar water heating system having flat plate collector, specified by Bureau of Indian Standard (BIS) of capacity 100 lpd is taken [64]. The Description of Component of solar water heating systems may be found anywhere [65]. The energy analysis of renewable energy systems or any energy production systems can be performed by using process analysis, input–output analysis or net energy analysis method [66]. In this present study process analysis method has been considered for the evaluation of total energy embodied during 20 years of useful life time of the system. In this process, energy inputs in individual component are estimated. Energy embodied in individual components is estimated by the estimation of direct and indirect energy. This is taken into account for the entire process of manufacturing the finished component and maintenance during its useful lifetime. Monthly average daily radiation, temperature, relative humidity and the values of wind speed for different locations have been taken from the RET-Screen online weather database. The renewable energy outputs of the system and GHG-emission reduction for annual use of solar water heating system for different selected locations of India have been estimated using RETScreen–decision support software, developed and disseminated by renewable energy decision support centre, Canada [67]. The climate of India has been divided in six zones according to variation of its climatic conditions by Bansal and Minke [68]. However, this study has been undertaken for representative city of 28 states to analyze precise feasibility of installing of solar water heating system. Energy yield ratio and energy payback period has been estimated to judge the energetic viability of the system. Energy embodied in different components or the entire system and energy output are considered as primary energy to expedite a proper comparison and evaluation. For the sake of simplicity, estimation of energy embodied in solar water heating system some assumptions have been made. Firstly, while estimating energy input, manual labor is not taken into consideration because during manufacturing it does not have any impact on primary source of energy. In addition to this there may arise error and uncertainties while converting man hour into equivalent primary energy and process analysis has been carried out up to second level of regression. For evaluating the energetic feasibility of solar water heating system, two measures namely, energy yield ratio (EYR) and energy payback period (EPBP) have been considered.

2.1 Energy embodied analysis

Estimation of energy embodied under the considered method comprises several steps; Evaluation of quantity of primary material after the identification of different components of the system, followed by the estimation of the total energy input in individual component. Estimation of the total energy embodied in the system by the calculating useful life time of each of the individual component.

The life cycle embodied energy E_{emb} is calculated by the following expression:

$$E_{emb} = E_{direct} + E_{mate} + E_{om} \tag{1}$$

where, E_{direct} is the direct energy consumed during manufacturing process of different components and E_{mate} is the energy embodied for the materials in the system and is given by:

$$E_{mate} = \sum_{i=1}^{n} \xi_i m_i \tag{2}$$

E_{om} is the energy embodied in maintenance and periodic replacement the system and is given by:

$$E_{om} = \sum_{i=1}^{n} \left[\frac{UL_{dswh}}{FR_i} - 1 \right]^{+} (\xi_i m_i) \quad (3)$$

The "+" sign signifies the next higher whole number of the quantity inside the bracket.

2.2 Energy output analysis

The annual energy output of a system depends on design and operational parameters which include solar radiation availability, thermal performance of the collector type and collector tilt, storage tank, operating temperature and ambient conditions [69–72]. In this work RET-Screen system support software has been used for evaluation of energy output analysis.

2.3 Measured parameters of energetic performance

2.3.1 Energy yield ratio (EYR)

It is the ratio of lifecycle primary energy output of the system to the lifecycle energy embodied in the system and is expressed as:

$$EYR_{dswh} = \frac{\left[\left(\frac{E_{o,u}}{n_f} \right) (1 + \alpha) \right] UL_{dswh}}{lifecyle\ energy\ embodied} \quad (4)$$

2.3.2 Energy payback period ($EPBP_{dswh}$)

It is the time taken to recuperate the initial primary energy embodied in any system by the net annual primary energy saving by the use of the system. It is given by:

$$EPBP_{dswh} = \frac{(E_{direct} + E_{mat})}{\left[\left(\frac{E_{out}}{\eta_f} \right) (1 + \alpha) \right] - \left(\frac{E_{om}}{UL_{dswh}} \right)} \quad (5)$$

3. Results and discussion

Table 1 presents the energy embodied in manufacturing a flat plate collector of different absorber plates, viz., (a) Aluminum absorber plate having copper headers and risers (b) Copper absorber plate having copper headers and risers and (c) Steel absorber plate having copper header and risers. From the present table one may predict, the type of material and quantity required, and the corresponding embodied energy values (ξi) for three different types of collectors in manufacturing a 100 lpd solar water heating system. The value of ξi has been obtained from the literature [73]. It is observed that the collector with Aluminum absorber plate and copper header and riser has maximum energy embodied system (6382 MJ), which is followed by collector made up of steel absorber plate and copper header and riser (5899 MJ). Least energy-embodied system is found in collector made up of copper absorber plate header and riser (5815 MJ).

Flat plate collector component	Material	Quantity	Unit	Energy density (MJ/unit)	Embodied energy (MJ)
section frame (100x25)	Aluminium	4.25	kg	254	1080
sheet for back of the box (24 swg)	Aluminium	4.50	kg	254	1143
angle for box (1"x1"x 16 swg)	Aluminium	1.50	kg	254	381
foil for heat reflection (0.5mm)	Aluminium	1.50	kg	254	381
neelpop reviets (60nos)	Aluminium	0.03	kg	254	8
self-tapping screw	Steel	0.50	kg	50	25
insulation	Glass wool	0.12	m^3	114	14
glazing (4 mm thick)	Toughened	35.00	kg	30	1050
(a) absorber plate (0.71 mm thick)	Aluminium	4.46	kg	254	1133
(b) absorber plate (34 swg)	Copper	4.25	kg	133	565
(c) absorber plate (0.71 mm thick)	Steel	13	kg	50	650
riser tube (0.5" diameter,24 swg 10nos)	Copper	4.00	kg	133	532
header tube (1" diameter,22 swg 2 nos)	Copper	2.25	kg	133	299
flanges (4 nos, 80 mm outer diameter)	Brass	0.80	kg	133	106
beading for glass sealing	Rubber	1.50	kg	130	195
black paint		0.50	kg	72	36
Total (a) with aluminium absorber plate and copper headers and risers					6382
Total (b) with copper absorber plate, headers and risers					5815
Total (c) with steel absorber plate and copper headers and risers					5899

Table 1.
Energy embodied in manufacturing a flat plate collector of different absorber plates.

Total energy embodied in balance of the system was found to be 2924 MJ. Energy embodied estimated values of 625.16, 636 and 1219.16 MJ were found, respectively, for storage tank, stand and pipeline (**Table 2**).

From **Table 3**, one can predict the required energy of the system during its useful life time for three collector types and on the basis of different considered scenarios. The components of solar water heating system viz. storage tank, absorber plate, outer box, etc., have long life time. However, other subsidiary components may require replacement in the 20 years of useful life time of the system due to their short life time. Maximum energy requirement is found in case of glass whereas minimum for the insulation. Total estimated values of embodied energy in a complete system were found to be 9306, 8739 and 8823 MJ, respectively, in case of Cu-Cu, Al-Cu and Steel-Cu collector. One may also predict from the table that about 77,

System component	Material	Quantity	Unit	Energy density (MJ/unit)	Embodied energy (MJ)
Storage tank					
tank	Stainless Steel	12.50	kg	50	625
insulation	Glass wool	0.55	m3	114	62.7
cladding	Aluminium	1.50	kg	254	381
Stand					
angle	Steel	12.00	kg	50	600
paint		0.50	kg	72	36
Pipeline (20")	GI	20.00	kg	50	1000
insulation	Glass wool	0.14	m3	114	15.96
cladding	Aluminium	0.80	kg	254	203.2
					2924

Table 2.
Estimated energy input values in manufacturing the subsidiary components of the system.

Material replacement	Quantity	Unit	Energy Intensity (MJ/unit)	Optimistic scenario		Most probable		Pessimistic	
				FR_i (Years)	E_{om} (MJ)	FR_i (Years)	E_{om} (MJ)	FR_i (Years)	E_{om} (MJ)
Glass	35	Kg	30	10	1050	7	2100	5	3150
Rubber beading/gaskets	1.5	Kg	130	10	195	7	390	5	585
Paint	1	litre	72	7	144	5	216	3	432
Insulation	0.81	m3	114	10	92.34	7	184.68	5	277
Total					1481		2891		4444
Annual energy requirement in maintenance					74		145		222
Life cycle energy embodied	Cu-Cu		9306		10787		12197		13750
	Al-Cu		8739		10220		11629		13183
	Steel-Cu		8823		10305		11714		13267

FR_i= frequency of replacement
E_{om}=energy embodied in periodic replacement and maintenance

Table 3.
Lifecycle embodied energy in a 100 lpd solar water heating system (Useful life time = 20 years).

145 and 222 MJ energy is required for optimistic, most probable and pessimistic scenarios, respectively, for the annual maintenance of the system.

Energy output through solar water heating system at different locations of India for the annual use and use of 5.5 months per year of the system has been shown in **Figure 1**. Monthly average daily radiation in the plane of solar collector (kWh/m^2/d) has been evaluated on the basis of monthly average daily radiation on horizontal surface (kWh/m^2/d), monthly average temperature (°C), monthly average relative humidity (%) and monthly average wind speed (m/s). In addition to this, evaluation of energy output for specific location is based on different parameters viz. slope of collector of the solar water heating system was taken equivalent to latitude of the location. Solar collector of area 2 m^2, Fr (τα) coefficient of 0.85, wind correction for Fr (τα) of 0.040, Fr UL coefficient 11.56 (W/m^2)/°C, wind correction for Fr UL 4.37 (J/m^3)/°C, pipe diameter of 10 mm, piping and solar tank losses of 1%, losses due to snow and/or dirt of 2%, horizontal distance from mech. Room to collector of 5 m and horizontal distance of floors from mech. Room to collector of 2 m have been taken, heat exchanger/antifreeze protection was not considered, for the analysis of energy output.

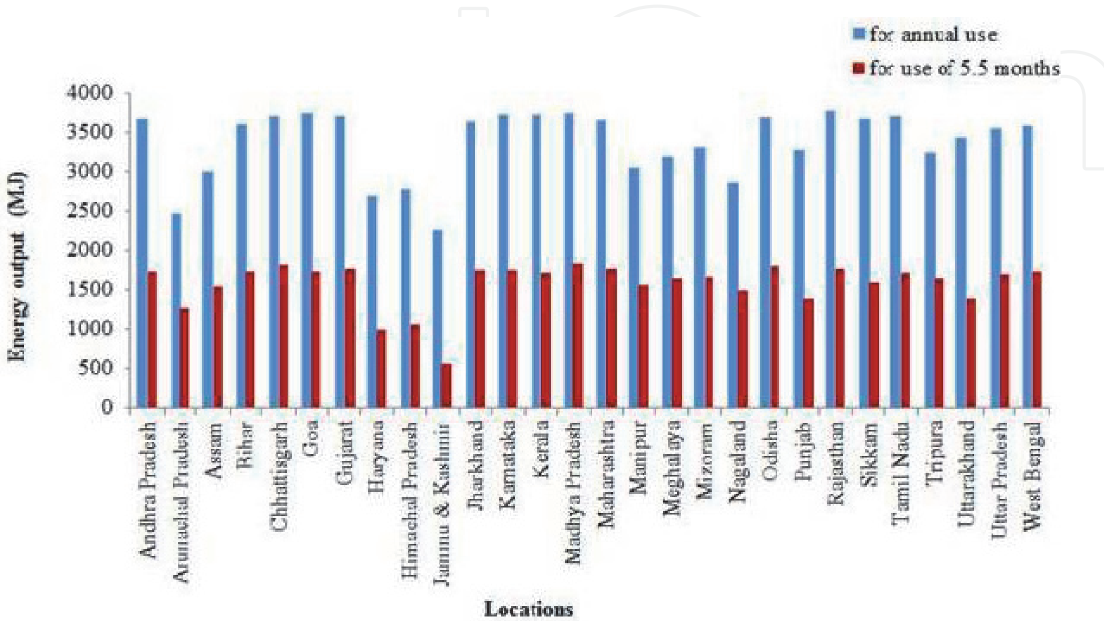

Figure 1.
Energy output through SWHS at different locations of India for annual use and of 5.5 months.

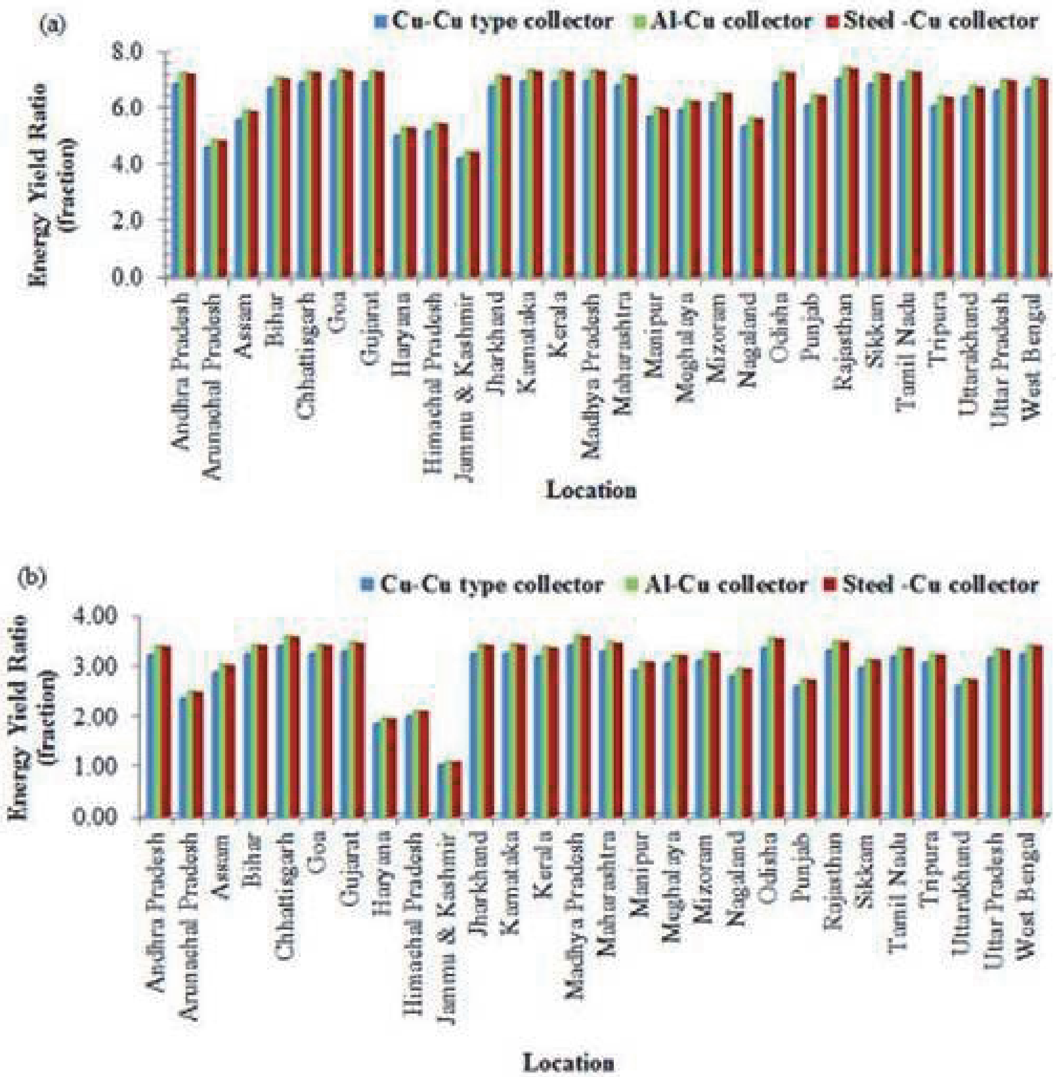

Figure 2.
EYR values for different locations of India of 20 years of useful lifetime of SWHS in case of Optimistic scenario for (a) annual use (b) use of 5.5 months per year.

The minimum value of energy output of 2258 MJ for Jammu Kashmir and maximum value of 3781 MJ was found in case of Rajasthan for the annual use of the solar water heating system. However, use of 5.5 months of the solar water heating system, the minimum and maximum value of energy output of 555 and 1833 MJ, respectively, has been found for the locations Jammu Kashmir and Madhya Pradesh. The lower value of energy output in Jammu and Kashmir as compared to other locations is due to relatively poor weather conditions.

The variation of energy yield ratio (EYR) in case of Cu-Cu, Al-Cu and Steel-Cu collector types for different locations of India has been shown in **Figures 2–4**, for 20 years of useful lifetime of the solar water heating system. In this perspective, on the basis of different adopted scenarios viz., optimistic, most probable and pessimistic, detailed location wise graphical representation has been considered for the feasibility analysis of the system of its annual use and use of 5.5 months in a year. From these figures, one may predicts that, for annual use of solar water heating system, in all locations for the selected collector types and for different scenarios, the energy yield ratio is greater than one. This signifies that the installation of solar water heating system in these locations is energetically feasible. The use of system for selected months in different locations of India has also been found feasible in terms of energy yield ratio expect Jammu and Kashmir. However, due to cold

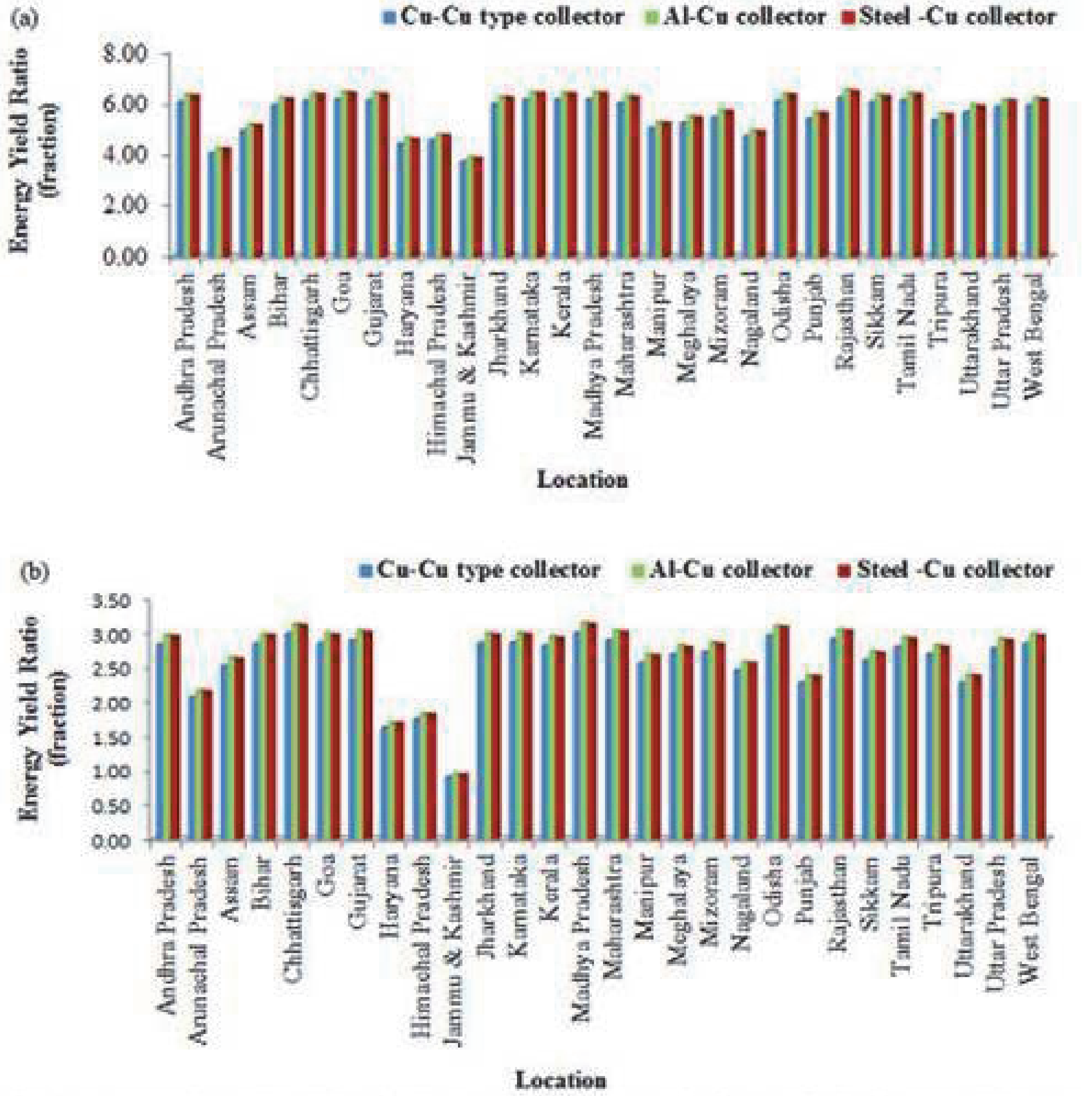

Figure 3.
EYR values for different locations of India of 20 years of useful lifetime of SWHS in case of Most Probable scenario for (a) annual use (b) use of 5.5 months per year.

climatic conditions of said location, there is requirement of annual use or for commercial applications of solar water heating system.

Figures 5–**7** depicts the energy payback period for 28 locations in India for the two utilization conditions of the system, i.e., for the use of the system 5.5 months in a year and use of the system for entire year. Evaluation of energy payback period has also been taken for 20 years of useful life time of the system, collectors used and scenarios as considered in the estimation of EYR. From these figures, one may also observe that, the annual use of the system and use of 5.5 months in a year, the value of energy payback period is less than its useful lifetime, in case of different collector types and scenarios. However, the use of the system for 5.5 months in a year, energy payback period is found greater than its useful lifetime for Jammu and Kashmir.

Estimated values of GHG-emission reduction for annual use of solar water heating system has been shown in **Table 4** for different locations of India. GHG-emission mitigation potential of solar water heating system has been evaluated on the basis of energy delivered by the system, and the replacement of solar water heating system with different fuels based systems. Base case GHG-emission factor (tCO_2/MWh) in case of natural gas, coal, oil, diesel oil, biomass and propane has been taken 0.491, 0.491, 1.018, 0.975, 0.030 and 0.552, respectively. The value of

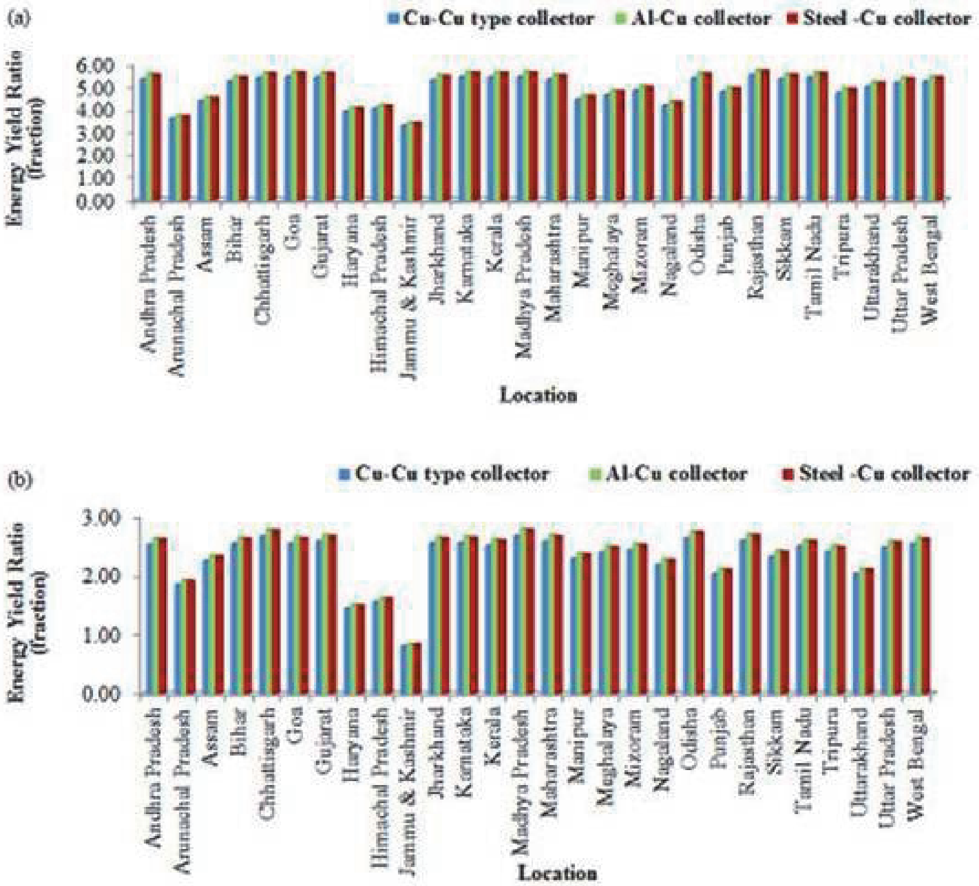

Figure 4.
EYR values for different locations of India of 20 years of useful lifetime of SWHS in case of Pessimistic scenario for (a) annual use (b) use of 5.5 months per year.

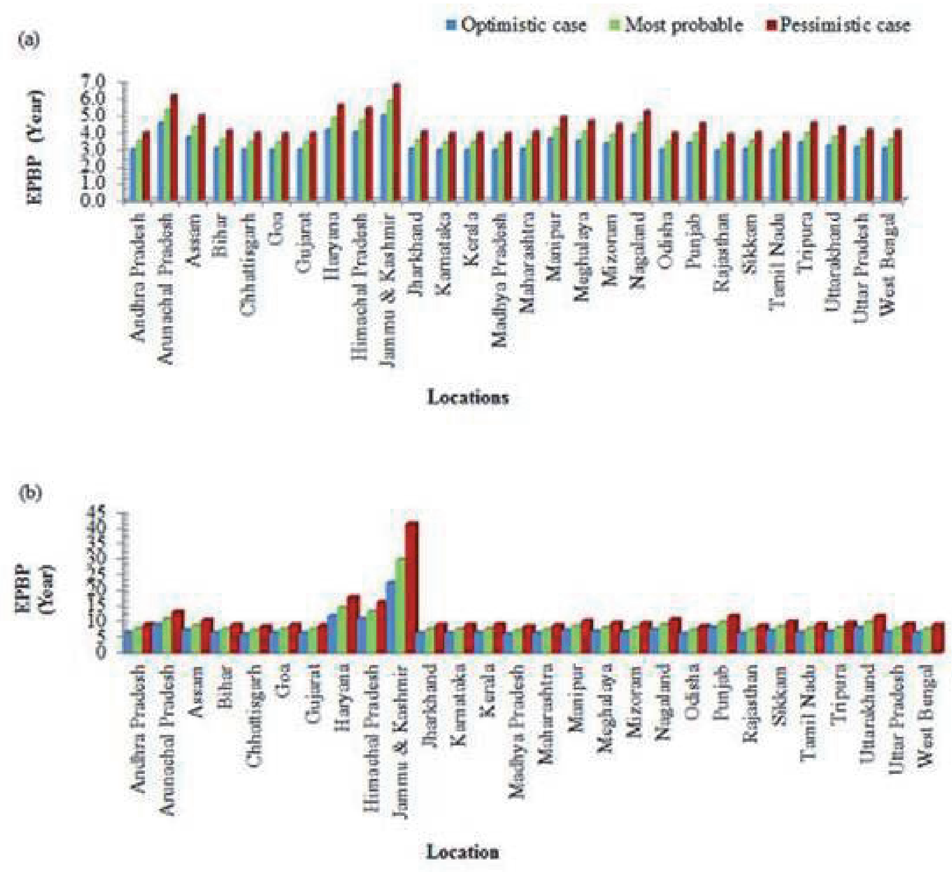

Figure 5.
EPBP values for 20 years of useful lifetime of SWHS at different locations of India in case of Cu-Cu collector material (a) for its annual use (b) for its use of selected months.

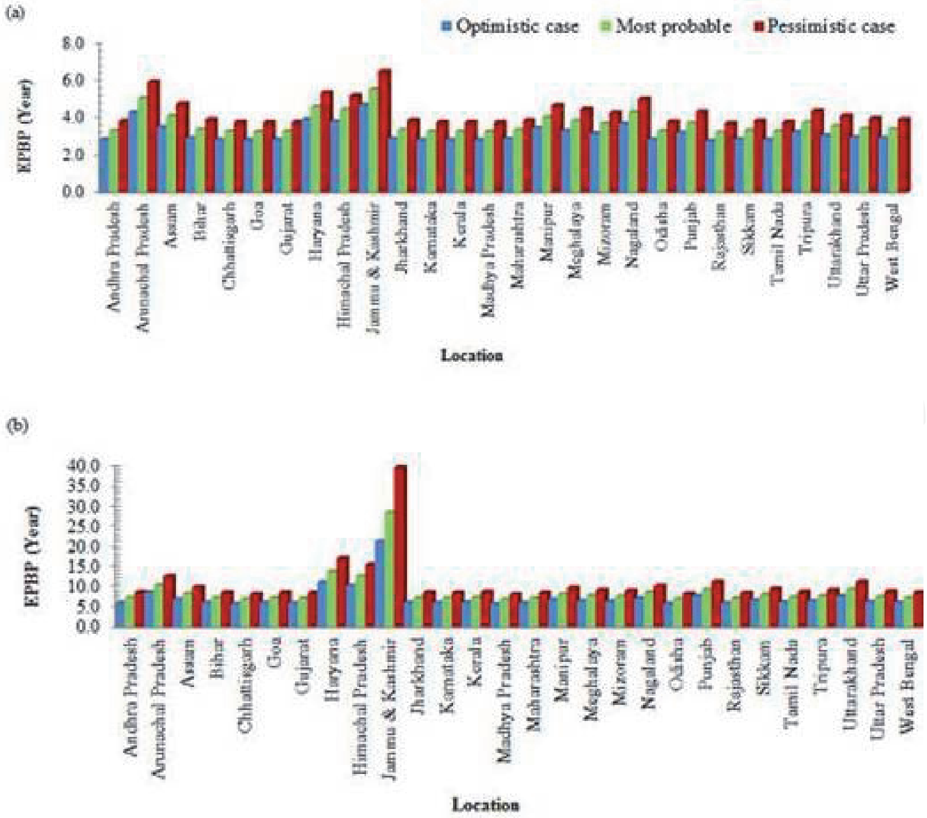

Figure 6.
EPBP values for 20 years of useful lifetime of SWHS at different locations of India in case of Al-Cu collector material (a) for its annual use (b) for its use of selected months.

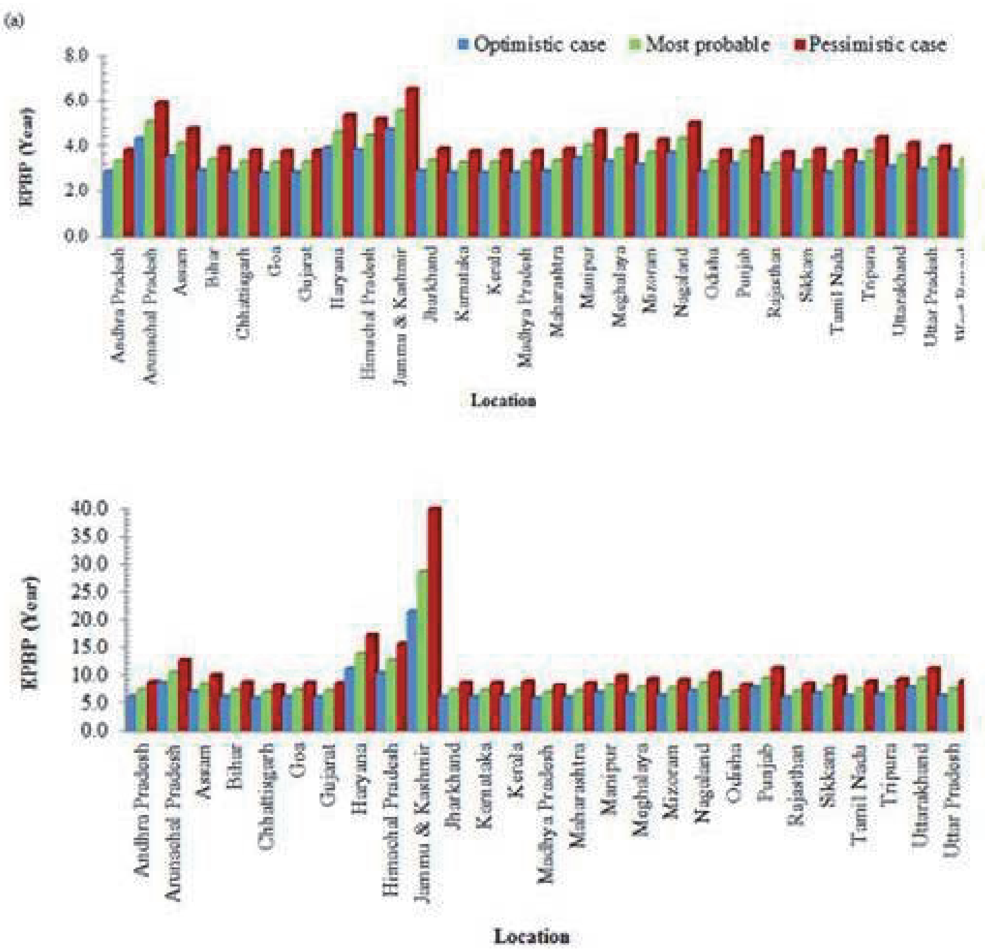

Figure 7.
EPBP values for 20 years of useful lifetime of SWHS at different locations of India in case of Steel-Cu collector material (a) for its annual use (b) for its use of selected months.

Location	GHG emission reduction (tCO2)= Base case GHG-emission factor (tCO₂/MWh x End use energy delivered (MWh) + Proposed case GHG-emission factor (tCO₂/MWh)						
	End use energy delivered (MWh)	Base case system (fuel type)					
		Natural gas	Coal	oil	Diesel oil	Biomass	Propane
		Base case GHG emission factor (tCO2/MWh)					
		0.491	1.069	1.018	0.975	0.030	0.552
		Annual GHG emission reduction (tCO₂/year)					
Andhra Pradesh	1.02	0.50	1.09	1.04	1.00	0.03	0.56
Arunachal Pradesh	0.69	0.34	0.73	0.70	0.67	0.02	0.38
Assam	0.83	0.41	0.89	0.85	0.81	0.02	0.46
Bihar	1.00	0.49	1.07	1.02	0.98	0.03	0.55
Chhattisgarh	1.03	0.51	1.10	1.05	1.00	0.03	0.57
Goa	1.04	0.51	1.11	1.06	1.01	0.03	0.57
Gujarat	1.03	0.51	1.10	1.05	1.01	0.03	0.57
Haryana	0.75	0.37	0.80	0.76	0.73	0.02	0.41
Himachal Pradesh	0.77	0.38	0.82	0.78	0.75	0.02	0.42
Jammu & Kashmir	0.63	0.31	0.67	0.64	0.61	0.02	0.35
Jharkhand	1.01	0.50	1.08	1.03	0.98	0.03	0.56
Karnataka	1.04	0.51	1.11	1.06	1.01	0.03	0.57
Kerala	1.03	0.51	1.10	1.05	1.01	0.03	0.57
Madhya Pradesh	1.04	0.51	1.11	1.06	1.01	0.03	0.57
Maharashtra	1.01	0.50	1.08	1.03	0.99	0.03	0.56
Manipur	0.85	0.42	0.91	0.86	0.83	0.03	0.47
Meghalaya	0.88	0.43	0.95	0.90	0.86	0.03	0.49
Mizoram	0.92	0.45	0.98	0.94	0.90	0.03	0.51
Nagaland	0.80	0.39	0.85	0.81	0.78	0.02	0.44
Odisha	1.03	0.50	1.10	1.05	1.00	0.03	0.57
Punjab	0.91	0.45	0.97	0.93	0.89	0.03	0.50
Rajasthan	1.05	0.52	1.12	1.07	1.02	0.03	0.58
Sikkam	1.02	0.50	1.09	1.04	0.99	0.03	0.56
Tamil Nadu	1.03	0.51	1.10	1.05	1.01	0.03	0.57
Tripura	0.90	0.44	0.96	0.92	0.88	0.03	0.50
Uttarakhand	0.95	0.47	1.02	0.97	0.93	0.03	0.53
Uttar Pradesh	0.95	0.47	1.02	0.97	0.93	0.03	0.53
West Bengal	1.00	0.49	1.07	1.02	0.97	0.03	0.55

Table 4.
Estimated values of GHG-emission reduction for annual use of the system.

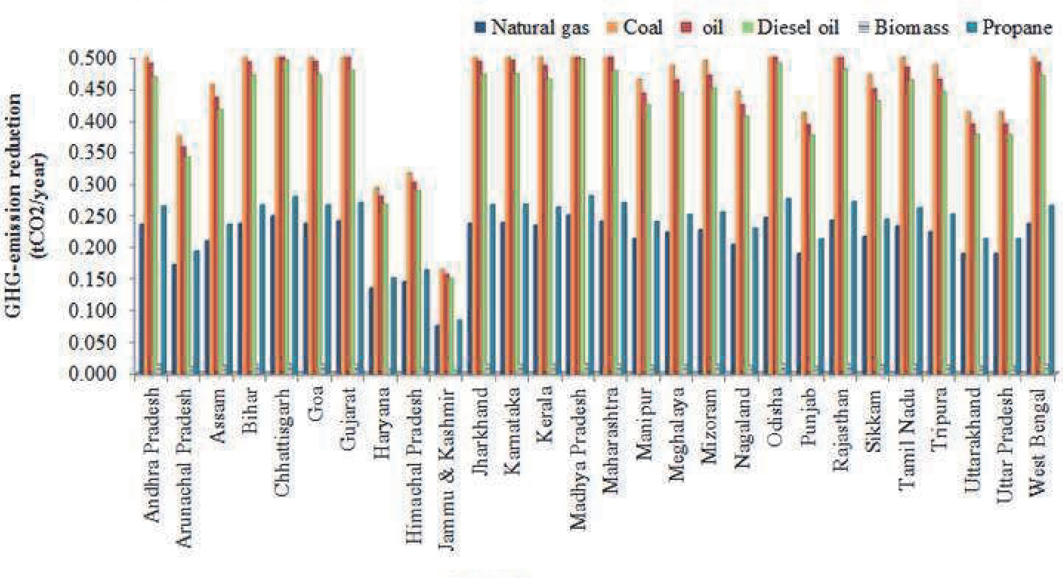

Figure 8.
Estimated values of GHG-emission reduction of using the system for selected months in a year.

proposed case emission factor has been taken as zero in case of solar water heating system, based on the fact that there is no pollution during the operation of the system. From **Table 4**, one may depict the annual variation range of 0.31 tCO_2 to 0.51 tCO_2, 0.67 tCO_2 to 1.12 tCO_2, 0.70 tCO_2 to 1.06 tCO_2, 0.02 tCO_2 to 0.03 tCO_2 and 0.35 tCO_2 to 0.58 tCO_2 in case of Natural gas, coal, oil, diesel oil, biomass and propane, respectively, for different selected location of India. Estimated values of GHG-emission reduction of using the system for 5.5 months in a year for different locations has been shown in **Figure 8**.

4. Conclusions

In solar water heating system having glazed flat collector, collector with copper absorber plate and headers and risers made of copper required minimum energy in compare to Steel-Copper and Aluminum-Cooper. Being the feasibility of the system does depending upon the availability of solar radiation of that particular location; it is also depending upon the utilization of the system by end user. So the present study on the basis of different scenarios viz. optimistic, most probable and pessimistic may give more classified information to the end users, researchers, academician and industrialist. Significant amount of GHG emission mitigation potential of the system have been estimated for different locations. Further the amount of GHG emission or mitigation does depend on the utilization of solar water heating system and use of fuel type by end users of those particular locations.

Acknowledgements

Authors are thankful to the Ministry of New and Renewable Energy Sources (MNRE), India, for funding the investigations and Solar Energy Centre, Gual Pahari, Gurgaon (SEC), India, for providing research facilities.

Nomenclature

ξ_i	energy intensity of the i^{th} component of the material (in MJ/mass or MJ/volume)
m_i	mass per unit volume of the i^{th} component
n	total number of components in the system
UL_{dswh}	expected useful life of the system
FR_i	frequency of replacement of the i^{th} component
n_f	efficiency of utilization in the corresponding heating device
α	fraction of the process energy required to make the fuel available to the user

Author details

Bhupendra Singh Rawat[1], Pradeep Chandra Pant[2], Poonam Negi[3]* and Bharti Ramola[3]

1 Department of Physics, Faculty of Applied Sciences, Uttaranchal University, Dehradun, UK, India

2 Ministry of New and Renewable Energy (MNRE), New Delhi, India

3 Department of Chemistry, Faculty of Applied Sciences, Uttaranchal University, Dehradun, UK, India

*Address all correspondence to: poo.chm20@gmail.com

References

[1] Palensky P, Dietrich D. Demand side management: Demand response, intelligent energy systems, and smart loads. IEEE Transactions on Industrial Informatics. 2011;**7**(3):381-388

[2] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews. 2011;**15**: 150-168

[3] Petrecca G. Industrial Energy Management: Principles and Applications. Massachusetts: Kluwer Academic Publisher; 1993

[4] Gielen D, Taylor P. Indicators for industrial energy efficiency in India. Energy. 2009;**34**:962-969

[5] Taner T. Energy management for Turkish Industry (in Turkish) [MSc thesis]. Denizli: Pamukkale University Institute of Science; 2002

[6] Streimikiene D, Burbeikis J, Punys P. Review of renewable energy use in Lithuania. Renewable and Sustainable Energy Reviews. 2005;**9**:29-49

[7] Balusamy T, Sadhishkumar S. Performance improvement in solar water heating systems—A review. Renewable and Sustainable Energy Reviews. 2014;**37**:191-198

[8] Proctor D, Morse RN. Solar energy for the Australian food processing industry. Solar Energy. 1977;**19**:63-72

[9] Kalogirou SA. The potential of industrial process heat applications. Applied Energy. 2003;**76**:337-361

[10] Islam MR, Sumathy K, Khan SU. Solar water heating systems and their market trends. Renewable and Sustainable Energy Reviews. 2013;**17**:1-25

[11] Timilsina GR, Kurdgelashvili L, Narbel PA. A Review of Solar Energy—Markets, Economics and Policies. Policy Research Working Paper 5845. The World Bank, Development Research Group, Environment and Energy Team. Washington, DC: World Bank; 2011. Available from: http://documents.worldbank.org/curated/en/5460914 68178728029/A-review-of-solar-energy-markets-economics-and-policies

[12] Eléonore Q. Overview of Sustainable Renewable Energy Potential of India—2010. Report Updated by Avinash HN, Palak Timbadiya Research Associates. San Diego, California, USA: Global Energy Network Institute (GENI); 2010

[13] Annual Report. New Delhi: Ministry of Non-Conventional Energy Sources. 2002. Available from: http://mnes.nic.in

[14] Naidu BSK. Indian scenario of renewable energy for sustainable development. Energy Policy. 1996; **24**(6):575-581

[15] Webb M, Pearce D. The economics of energy analysis. Energy Policy. 1975; **3**:318-333

[16] Mathur J, Bansal N. Analysis of selected renewable energy options for India. Energy Sources. 2001;**23**:877-888

[17] Vettrivel H, Mathiazhagan P. Comparison study of solar flat plate collector with single and double glazing systems. International Journal of Renewable Energy Research. 2017;**7**(1): 266-274

[18] Hottel HC, Whillier A. Evaluation of Flat-Plate Collector Performance. Tucson, AZ, USA: University of Arizona Press; 1958

[19] Klein SA. Calculation of flat-plate collector utilizability. Solar Energy. 1978;**21**(8):393-402

[20] Klein SA, Beckman WA, Duffie JA. A design procedure for solar heating systems. Solar Energy. 1976;**18**:113-127

[21] Atipoang N, Chansena C, Kiatsiriroat T. Performance analysis of solar water heater combined with heat pump using refrigerant mixture. Applied Energy. 2009;**86**(5):748-756

[22] Ruchi S, Sumathy K, Erickson P, Gong J. Recent advances in the solar water heating systems: A review. Renewable and Sustainable Energy Reviews. 2013;**19**:173-190

[23] Matuska T, Vladimir Z, Juliane M. Detailed modelling of solar flat-plate collectors with design tool kolektor 2.2. In: 11th International IBPSA Conference, Scotland; 2009. pp. 2289-2296

[24] Agbo SN, Okoroigwe EC. Analysis of thermal loses in the flat-plate collector of a thermosyphon solar water heater. Research Journal of Physics. 2007;**1**:35-41

[25] Pillar PK, Agarwal RC. Factors influencing solar energy collector efficiency. Applied Energy. 1981;**8**: 205-213

[26] Buchberg H, Catton I, Edwards DK. Natural convection in enclosed spaces—A review of application to solar energy collection. Journal of Heat Transfer. 1976;**98**(2):182-188

[27] Sekhar YR, Sharmaand KV, Basaveswara RM. Evaluation of heat loss coefficients in solar flat plate collectors. ARPN Journal of Engineering and Applied Sciences. 2009;**4**(5):15-19

[28] Agbo SN, Unachukwu GO. Performance evaluation and optimization of the NCERD thermosyphon solar water heater. In: Proceedings of the World Renewable Energy Congress; August 19–25; Florence, Italy; 2006

[29] Duffie JA, Beckman WA. Solar Energy Thermal Processes. New York: John Wiley Inc.; 1974

[30] Eisenmann W, Vajen K, Ackermann H. On the correlations between collector efficiency factor and materials content of parallel flow flat plate solar collectors. Solar Energy. 2004;**76**:381-387

[31] Malhotra A, Garg HP, Palit A. Heat loss calculation of flat plate solar collectors. Journal of Thermal Engineering. 1981;**2**:59-62

[32] Mumah SN. Transient response of thermosyphon solar collectors. Solar Energy. 1995;**24**:55-61

[33] Morrison GL, Ranatunga DB. Sizing and performance evaluation of a flat-plate collector for a solar absorption refrigeration system. Nigerian Journal of Solar Energy. 1980;**13**:67-75

[34] Yeh HM, Ho CD, Yeh CW. Effect of aspect ratio on the collector efficiency of sheet and tube solar water heaters with the consideration of hydraulic dissipated energy. Renewable Energy. 2003;**28**:1575-1586

[35] Natural Resources Canada. RETScreen International. Available from: http://www.retscreen.net

[36] TRNSYS: Transient Systems Simulation Program. 2010. Available from: http://sel.me.wisc.edu/trnsys/

[37] POLYSUN: Simulation Software for Solar Thermal Systems. 2010. Available from: http://www.solarconsulting.us/polysun.html

[38] TSOL, Dynamic Simulation Programme for the Design and Optimisation of Solar Thermal Systems. 2010. Available from: http://www.valentin.de/

[39] Kalogirou SA. Optimization of solar systems using artificial neural-networks

and genetic algorithms. Applied Energy. 2004;**77**:383-405.17

[40] Kulkarni GN, Kedare SB, Bandyopadhyay S. Design of solar thermal systems utilizing pressurized hot water storage for industrial applications. Solar Energy. 2008;**82**(18): 686-699

[41] Kim YD, Thu K, Bhatia HK, Bhatia CS, Ng KC. Thermal analysis and performance optimization of a solar hot water plant with economic evaluation. Solar Energy. 2012;**86**(19):1378-1395

[42] Atia DM, Fahmy FH, Ahmed NM, Dorrah HT. Optimal sizing of a solar water heating system based on a genetic algorithm for an aquaculture system. Mathematical and Computer Modelling. 2012;**55**(20):1436-1449

[43] Bornatico R, Pfeiffer M, Witzig A, Guzzella L. Optimal sizing of a solar thermal building installation using particle swarm optimization. Energy. 2012;**41**(21):31-37

[44] Cheng Hin JN, Zmeureanu R. Optimization of a residential solar combisystem for minimum life cycle cost, energy use and exergy destroyed. Solar Energy. 2014;**100**(22):102-113

[45] Myeong JK. Analysis and optimization design of a solar water heating system based on life cycle cost using a genetic algorithm. Energies. 2015;**8**:11380-11403. DOI: 10.3390/en81011380

[46] Matrawy KK, Farkas I. New technique for short term storage sizing. Renewable Energy. 1997;**11**:129-141

[47] Loomans M, Visser H. Application of the genetic algorithm for optimization of large solar hot water systems. Solar Energy. 2002;**72**(5): 427-439

[48] Krause M, Vajen K, Wiese F, Ackermann H. Investigation on optimizing large solar thermal systems. Solar Energy. 2002;**73**:217-225

[49] Bailey RA. Net energy analysis of eight technologies to provide domestic hot water heat. Energy. 1981;**983**:6

[50] Lund PD, Kangas MT. Net energy analysis of district solar heating with seasonal heat storage. Energy. 1983;**8**: 813

[51] Hernandez P, Kenny P. Net energy analysis of domestic solar water heating installations in operation. Renewable and Sustainable Energy Reviews. 2012; **16**:170-177

[52] Shahzada M, Nawaz N, Heliyo SA. Energy security for socioeconomic and environmental sustainability in Pakistan. Heliyon. 2018;**4**:e00854. DOI: 10.1016/j.heliyon.2018.e00854

[53] Denholm P. The Technical Potential of Solar Water Heating to Reduce Fossil Fuel Use and Greenhouse Gas Emissions in the United States. Technical Report NREL/TP-640-41157. Battelle,USA: National Renewable Energy Laboratory; 2007

[54] Purohit P, Michaelowa A. CDM potential of solar water heating systems in India. Solar Energy. 2008;**82**:799-811

[55] Han J, Mol APJ, Lu Y. Solar water heaters in China: A new day dawning. Energy Policy. 2010;**38**:383-391

[56] Crawford RH, Treloar GJ. Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. Solar Energy. 2004;**76**:159-163

[57] Ardente F, Beccali G, Cellura M, Lo Brano V. Life cycle assessment of a solar thermal collector. Renewable Energy. 2005;**30**:1031-1054

[58] Battisti R, Corrado A. Environmental assessment of solar

thermal collectors with integrated water storage. Journal of Cleaner Production. 2005;**13**:1295-1300

[59] Asif M, Currie J, Muneer T. Comparison of aluminium and stainless steel built-in-storage solar water heater. Building Services Engineering Research and Technology. 2007;**28**:337-346

[60] Kalogirou S. Thermal performance, economic and environmental life cycle analysis of thermosyphon solar water heaters. Solar Energy. 2009;**83**:39-48

[61] Kalogirou S. Environmental benefits of domestic solar energy systems. Energy Conversion and Management. 2004;**45**:3075-3092

[62] Mathur J, Bansal N. Energy analysis of solar water heating systems in India. The International Journal of Life Cycle Assessment. 1999;**4**:113-116

[63] Marimuthu CL, Kirubakaran V. Carbon payback period and energy payback period for solar water heater V.2. International Research Journal of Environmental Sciences. 2014;**3**(2): 93-98

[64] BIS. Indian Standard-Solar Flat Plat Collector-Specification IS 12933 (Part 5). New Delhi, India: Bureau of Indian Standards; 1992

[65] Pant PC, Mishra AK, Kandpal TC. Energetics of solar water heating system. In: Proceeding of 3rd International Conference on Solar Radiation and Day Lighting (SOLARIS 2007) organized by Centre for Energy Studies, Indian Institute of Technology, Delhi; New Delhi, India; 2007. pp. 509-516

[66] Chapman PF. Energy costs: A review of methods. Energy Policy. 1974; **2**(2):91-103

[67] RET-Screen Software, Government of Canada, Natural Resources Canda's CANMET Energy Diversification Research Laboratory (CEDRL). 2000. Available from: http://rescreen.gc.ca

[68] Bansal NK, Minke G. Climatic Zones and Rural Housing in India. Germany: Scientific Series of International Bureau; 1995

[69] Morrison GL, Braun JE. System modeling and operation characteristics of thermosyphon solar water heaters. Solar Energy. 1985;**34**:389-405

[70] Fanney AH, Klein SA. Performance of solar domestic hot water systems at the National Bureau of Standards—Measurements and predictions. ASME Journal of Solar Energy Engineering. 1983;**105**:311-321

[71] Morrison GL, Tran HN. Simulation of the long term performance of thermosyphon solar water-heaters. Solar Energy. 1984;**33**:515-526

[72] Shariah A, Shalabi B. Optimal design for a thermosyphon solar water heater. Renewable Energy. 1997;**11**:351-361

[73] Boustead I, Hankok GF. Handbook of Industrial Energy Analysis. Chichester West Sussex, England: Ellis Horwood Limited; 1979