Estimation of solar collector area for water heating in buildings of Malaysia

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Abstract. Solar thermal energy (STE) utilization for water heating at various sectorial levels became popular and still growing especially for buildings in the residential area. This paper aims to study and identify the solar collector area needed based on the user requirements in an efficient manner. A step by step mathematical approach is followed to estimate the area in Sq. m. Four different cases each having different hot water temperatures (45°, 50°C, 55°C, and 60°C) delivered by the solar water heating system (SWHS) for typical residential application at Kuala Lumpur City, Malaysia is analysed for the share of hot and cold water mix. As the hot water temperature levels increased the share of cold water mix is increased to satisfy the user requirement temperature, i.e. 40°C. It is also observed that as the share of hot water mix is reduced, the collector area can also be reduced. Following this methodology at the installation stage would help both the user and installers in the effective use of the solar resource.

1. Introduction

Residential water heating is an important one that everyone has to adopt, this helps in controlling the effects caused by unseen pathogens on human life [1]. There are few conventional and nonconventional methods used for water heating. Conventional water heating is done mainly by burning charcoal, and wood. However, the use conventional fuels cause adverse effects like the release of greenhouse gases (GHG), dust pollutions, etc. To avoid the serious and dangerous effects (climate change, global warming, and environmental pollutions, etc.) of GHG emissions, mitigation methods are to be practiced [2-4]. The best way of avoiding this GHG emission is shifting towards solar energy. Solar energy can be harnessed for electricity generations to cater the ever-increasing energy demands relating to various applications like street lighting, water pump sets, University buildings, industries areas, residential houses, and powering airports. Several authors have also conducted research studies to analyze the performance the PV systems when they are integrated into a building and studies related to floating PV systems are also emerging. The second way of harnessing the solar energy is the use of thermal collectors, where the solar energy is converted into useful thermal energy in a variety of applications by means of solar collectors [5, 6]. Sizing of the SWHS requires a lot of input data, which may not be possible to get all the times. Moreover the efficiently designed system will perform better in delivering the hot water. The problem of identifying the collector areas required as per the share of cold and hot water mix at required temperature levels of the users is still unaddressed. In this paper, an application of solar thermal energy conversion is chosen i.e., solar water

heating systems (SWHS) to reduce the energy consumption in the residential zones is considered. This paper is aimed to propose a simple method for estimating the solar collector's area based on the user input requirement and as well the collector delivery water temperatures.

2. Description of solar water heating system

Solar water heating system (SWHS) works by converting the solar energy into heat energy with the help of thermal collectors. These collectors will face in the direction of the sun to capture as much as sun's energy. These were mainly used for heating water in residential areas and industrial sectors. The components of SWHS are a solar collector, storage tank, circulating tubes, pumps, sensors and controls. The schematic view of the solar water heating system (SWHS) is shown in Figure 1. For most of the SWHS, flat plate solar thermal collectors were used. These collector devices were generally mounted on the building roof facing towards the sun. It is equipped with circulating tubes in it attached to the absorber plate of the collector. This helps in carrying the antifreeze solution or water for capturing the heat energy from the sun and deliver the same energy to the storage tank. The storage tank is a kind of modified heat exchanger with insulations providing no loss of heat energy to a maximum extent. This tank helps in storing the hot waters that are heated by the solar collectors. From the storage tanks, hot water is made to flow through the domestic taps or other means where users can access. Other components like pumps will help to pump the cold waters to the collector inlets and sensors and control are used to sense various parameters at the system level [7-13].
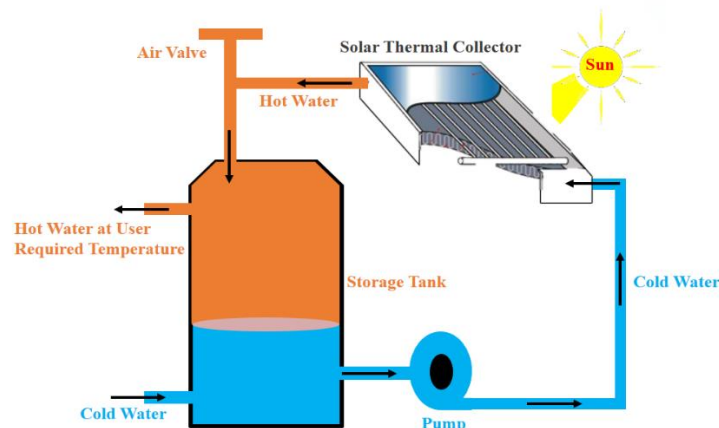

Figure 1. Schematic View of Solar Water Heating System (SWHS).

3. Methodology

3.1. Study location

Study location is chosen to be the Kuala Lumpur City in Malaysia. It is one among the 140 cities that are globally ranked by economic intelligence unit for best living conditions and its rank is 70 [14]. The weather conditions of Kuala Lumpur is tropical experiencing hot and humid climates with heavy rain falls all around the year. The water temperatures in Kuala Lumpur city will not have many variations. The maximum, minimum, and average water temperatures are 30.1°C, 29°C, and 27.1°C respectively shown in Figure 2. [15]. Monthly water temperature details in study location are shown in Table 1. Hot water consumption details for a typical residential family staying at Kuala Lumpur is considered for this study i.e. 840 Liter/day.

Table 1. Study location details.

Description	Value

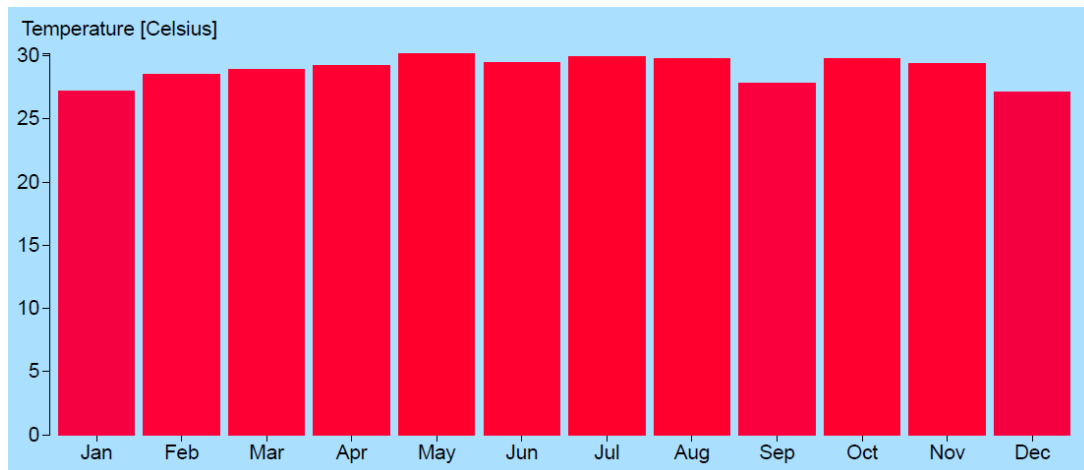| Name of the Study Location	Kuala Lumpur
Latitude	°C
Longitude	°C
Hot Water Consumption at the Site	840 Litre/day
Minimum Temperature of the Water	27.1 °C
Maximum Temperature of the Water	30.1 °C
Average Temperature of the Water	29 °C

Figure 2. Water Temperature at Kuala Lumpur City [15].

3.2. Calculation procedure

The following methodology is applied to estimate the suitable collector size required for heating water with the help solar thermal energy.

➢ Step-1: A survey based study is conducted to analyze the hot water consumption patterns per day at the study location.
➢ Step-2: Estimate the possible water losses during the process that is in the form of hot water losses.
➢ Step-3: Estimate the final hot water requirements per day considering the heat losses.
➢ Step-4: Calculate the share of the cold and hot waters to be mixed. This shared value depends on many other parameters such as hot water temperature possible in the solar collector, cold water temperature at the site, usable of hot water temperature requirement by the user.
➢ Step-5: Estimate the size of solar collector which depends up on the hot water share and the solar water heater maximum delivery capacity.
➢ Step-6: Size estimation of the storage tank to store the water.

3.3. Total hot water requirement

Total hot water requirement is calculated by conducting extensive surveys related to hot usage at a site [16] where solar water heating systems (SWHS) is about to propose or equip. The surveyed information cannot consider as the final value unless and until water loss parameter is considered. Hence, the total hot water requirement calculated using Eq. 1. [17] Will be the sum of the hot water requirements at the site plus water lost.

$$W_t = W_{r\_site} + W_l \qquad (1)$$

Where, W_t is the total hot water required in Litre after considering losses, W_{r_site} is the quantity of water used by number of households for typical tasks in Liter, and W_l is the water lost in Litre.

3.3.1. Hot water consumption details in a residential building. As said earlier, hot water consumptions are calculated based on the surveys conducted among the group of people or a group of apartments or a community. In this study, a typical urban residential building with 'n' number of person's and their water requirements are considered and tabulated in Table 2. This table shows that, residential building consumes hot water in different tasks i.e. 60 Litre per person per day for Bathing, 10 Litre per person per day for Wash Basin, 15 litres per person per day for Kitchen Wash, 10 Litre per person per day for Clothes Wash, 10 Litre per person per day for other usages.

Table 2. Water consumption details.

Description	Water/Person/Day (Litre)	No. of Persons (n)	Water Requirement at the Site (Litre/day)
Bathing	70	6	420
Wash Basin	15	6	90
Kitchen Wash	25	6	150
Clothes Wash	20	6	120
Others	10	6	60

$$W_{r\_site} = \left[\left(W_{task_1} \times n_1 \right) + \left(W_{task_2} \times n_2 \right) + \left(W_{task_3} \times n_3 \right) + \cdots\cdots\cdots + \left(W_{task_n} \times n_n \right) \right] \qquad (2)$$

Hot water requirement at the site is calculated with the help of Eq. 2. Hot water consumption can be defined to be the sum of the water consumed by households in all different tasks.

Where, W_{r_site} is the quantity of water used by a number of households for typical tasks in Litre n_1, $n_2, n_3 \ldots \ldots n_n$ are the number of persons in the residential house, $W_{task_1}, W_{task_2}, W_{task_3} \ldots \ldots W_{task_n}$ are the various tasks where hot water is used.

3.3.2. Water losses. As discussed earlier in a thermal energy system, loss factor is the most crucial one to be considered during the system analysis. As our application is heating water, there are possibilities for water losses in the form of heat or even sometimes leakage of the water itself. If this is not counted in water requirement section, there is the possibility of miss match between the final hot water requirements. Hence, in this study 20 % is considered as water loss percentage throughout the system [17]. The Effective amount of water that is to be added to W_{r_site} is calculated using Eq. 3.

$$W_l = \frac{Water\ Loss\ Percentage\ (\%)}{100} \times W_{r\_site} \qquad (3)$$

Where, W_l is the water lost in litre, and W_{r_site} is the quantity of water used by number of households for typical tasks in Litre.

3.4. Share of cold and hot water mix.
Once total hot water required is estimated, then the share of cold and hot water mix is calculated. Before calculating this, the ratio of cold water quantity to hot water quantity is to found using Eq. 4. Based on the obtained ratio from Eq. 4, [17] share of the cold and hot water is calculated using Eq. 5. And Eq. 6. Respectively.

$$\frac{Q_{water\_cold}}{Q_{water\_hot}} = \frac{T_{hot\_water\_SWHS} - T_{user\_required}}{T_{user\_required} - T_{cold\_water\_site}} \qquad (4)$$

$$S_{water\_cold} = \left(\frac{Q_{cold}}{Q_{cold}+Q_{hot}}\right) \times W_t \tag{5}$$

$$S_{water\_hot} = \left(\frac{Q_{hot}}{Q_{cold}+Q_{hot}}\right) \times W_t \tag{6}$$

Where, Q_{water_cold} is the quantity of cold water in Litre, Q_{water_hot} is the quantity of hot water in Litre, $T_{hot\_water\_SWHS}$ is the hot water temperature in °C that a solar water heating system delivers, $T_{user\_Required}$, is the required water temperature in °C by the users or the households, $T_{cold\_water\_site}$, is the cold water temperature in °C at the site or location, S_{water_cold} is the share of cold water mix in Litre, S_{water_hot} is the share of hot water mix in Litre, W_t is the total hot water required in Litre at a temperature of $T_{user\_Required}$.

3.5. Solar collector area
Solar collector area represents, space where the solar energy is made to concentrate and converted into useful energy. It is measured in Sq. m. The area of the collector is calculated using Eq. 7 [17].

$$Solar\ Collector\ Area = 2 \times \left(\frac{S_{water\_hot}}{W_{delivery\_SWHS}}\right) \tag{7}$$

Where, S_{water_hot} represents the share of hot water mix in Litre at a temperature of $T_{hot\_water\_SWHS}$, $W_{delivery\_SWHS}$ represents the quantity of hot water that can be delivered by solar water heating system in Litre.

3.6. Size of the storage tank.
Size of the storage tank is one of the essential parts of the solar water heating system, which is used for storing the waters. If a continuous usage of the hot water is possible, then the storage tank capacity can be minimised. If it is not the case of continuous usage, storage tank with capacity equals to water requirements can be built. Eq. 8. Is used to calculate the size of the storage tank.

$$Volume\ of\ the\ storage\ tank\ in\ Cubic\ meter = \frac{W_t}{1000} = \frac{W_{r\_site}+W_l}{1000} \tag{8}$$

4. Results and discussion
Results include the required collector areas estimations for heating the required quantity of water as per the user requirement. Here, maintaining the temperature as per user choice is an important aspect to be noticed. If the selected 250 litre system could deliver around 200 litres per day at certain temperatures, see in Figure 3. But most probably this temperature would vary based on the seasons and intensity of captured energy from the sun. Hence, four different temperatures of hot water in °C that a 250 litre system can deliver is considered and they are 45°C, 50°C, 55°C, and 60°C. Hence the results are briefed in four different cases. Also, the correlations between the calculated areas and temperature levels were estimated using curve fit options for result verification. Before proceeding into each case, the total water requirement is calculated using the Eq. 1, Eq. 2, and Eq. 3. From Eq. 2, the quantity of water used by the number households is calculated as follows:

$$W_{r_{site}} = [(W_{task_1} \times n_1) + (W_{task_2} \times n_2) + (W_{task_3} \times n_3) + \cdots\cdots\cdots + (W_{task_n} \times n_n)]$$

$$W_{r\_site} = [(70 \times 6) + (15 \times 6) + (25 \times 6) + (20 \times 6) + (10 \times 6)]$$

$$W_{r\_site} = (420 + 90 + 150 + 120 + 60) = 840\ Litre/day$$

From Eq. 3, the lost water in terms of heat and other leakage is estimated as follows considering lost percentage as 20 %.

$$W_l = \frac{Water\ Loss\ Percentage\ (\%)}{100} \times W_{r\_site}$$

$$W_l = \frac{20}{100} \times 840 = 168\ Litre/day$$

From Eq. 1, the total hot water required at 40°C is calculated as follows:

$$W_t = W_{r\_site} + W_l$$

$$W_t = 840 + 168 = 1008\ Litre/day$$

Hence, the total quantity of hot water required by the house holds is 1008 Litre/day at 40°C.

4.1. Case-I: 250 litre system delivers 200 litre at 45°C

In Case-I, if the 250-litre system can deliver hot water of 200 litres per day at 45°C temperatures, then the optimal collector area opted for meeting the user requirement is as follows.

From Eq. 4, cold water to hot water mix is calculated as follows. Now $T_{hot\_water\_SWHS}$ becomes 45°C, $T_{user\_required}$ is 40°C, and $T_{cold\_water\_site}$ is 27.1°C.

$$\frac{Q_{water\_cold}}{Q_{water\_hot}} = \frac{T_{hot\_water\_SWHS} - T_{user\_required}}{T_{user\_required} - T_{cold\_water\_site}}$$

$$\frac{Q_{water\_27.1°C}}{Q_{water\_45°C}} = \frac{45 - 40}{40 - 27.1} = \frac{5}{12.9}$$

From the ratio 5/12.9, the numerator becomes the cold water portion, and the denominator becomes the hot water portion, but to get the individual share in Litre, the following mathematical approach is adopted shown in Eq. 5 for cold water share, and Eq. 6 for hot water share.

$$S_{water\_cold} = \left(\frac{Q_{cold}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_27.1°C} = \left(\frac{5}{5 + 12.9}\right) \times 1008 = 281.564\ Litre/day$$

$$S_{water\_hot} = \left(\frac{Q_{hot}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_45°C} = \left(\frac{12.9}{5 + 12.9}\right) \times 1008 = 726.436\ Litre/day$$

From the above, it is clear that, to get hot water of 1008 Litre/day at 40°C, cold water of 281.564 Litre/day at 27.1°C has to be mixed with hot water of 726.436 Litre/day at a temperature of 45°C delivered by the SWHS. From Eq. 7, the solar collector area is estimated as follows:

$$Solar\ Collector\ Area = 2 \times \left(\frac{S_{water\_hot}}{W_{delivery\_SWHS}}\right)$$

$$Solar\ Collector\ Area = 2 \times \left(\frac{726.436}{200}\right) = 7.26436 \sim 7.3\ Sq.m$$

Solar collector area is found to be around 7.3 Sq. m for capturing the solar energy and convert into useful energy in the form of hot water i.e. 726.436 Litre/day at 45°C.

4.2. Case-II: 250 litre system delivers 200 litre at 50°C

In Case-II, if the 250-litre system can deliver hot water of 200 litres per day at 50°C temperatures, then the optimal collector area opted for meeting the user requirement is as follows.

From Eq. 4, cold water to hot water mix is calculated as follows. Now $T_{hot\_water\_SWHS}$ becomes 50°C, $T_{user\_required}$ is 40°C, and $T_{cold\_water\_site}$ is 27.1°C.

$$\frac{Q_{water\_cold}}{Q_{water\_hot}} = \frac{T_{hot\_water\_SWHS} - T_{user\_required}}{T_{user\_required} - T_{cold\_water\_site}}$$

$$\frac{Q_{water\_27.1°C}}{Q_{water\_50°C}} = \frac{50 - 40}{40 - 27.1} = \frac{10}{12.9}$$

From the ratio 10/12.9, the numerator becomes the cold water portion, and the denominator becomes the hot water portion, but to get the individual share in Litre, the following mathematical approach is adopted shown in Eq. 5 for cold water share, and Eq. 6 for hot water share.

$$S_{water\_cold} = \left(\frac{Q_{cold}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_27.1°C} = \left(\frac{10}{10 + 12.9}\right) \times 1008 = 440.175 \; Litre/day$$

$$S_{water\_hot} = \left(\frac{Q_{hot}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_50°C} = \left(\frac{12.9}{10 + 12.9}\right) \times 1008 = 567.825 \; Litre/day$$

From the above, it is clear that, to get hot water of 1008 Litre/day at 40°C, cold water of 440.175 Litre/day at 27.1°C has to be mixed with hot water of 567.825 Litre/day at a temperature of 50°C delivered by the SWHS. From Eq. 7, the solar collector area is estimated as follows:

$$Solar \; Collector \; Area = 2 \times \left(\frac{S_{water\_hot}}{W_{delivery\_SWHS}}\right)$$
$$Solar \; Collector \; Area = 2 \times \left(\frac{567.825}{200}\right) = 5.67825 \sim 5.7 \; Sq.m$$

Solar collector area is found to be around 5.7 Sq. m for capturing the solar energy and convert into useful energy in the form of hot water i.e. 577.825 Litre/day at 50°C.

4.3. Case-III: 250 litre system delivers 200 litre at 55°C

In Case-III, if the 250-litre system can deliver hot water of 200 litres per day at 55°C temperatures, then the optimal collector area opted for meeting the user requirement is as follows.

From Eq. 4, cold water to hot water mix is calculated as follows. Now $T_{hot\_water\_SWHS}$ becomes 55°C, $T_{user\_required}$ is 40°C, and $T_{cold\_water\_site}$ is 27.1°C.

$$\frac{Q_{water\_cold}}{Q_{water\_hot}} = \frac{T_{hot\_water\_SWHS} - T_{user\_required}}{T_{user\_required} - T_{cold\_water\_site}}$$

$$\frac{Q_{water\_27.1°C}}{Q_{water\_55°C}} = \frac{55 - 40}{40 - 27.1} = \frac{15}{12.9}$$

From the ratio 15/12.9, the numerator becomes the cold water portion, and the denominator becomes the hot water portion, but to get the individual share in Litre, the following mathematical approach is adopted shown in Eq. 5 for cold water share, and Eq. 6 for hot water share.

$$S_{water\_cold} = \left(\frac{Q_{cold}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_27.1°C} = \left(\frac{15}{15 + 12.9}\right) \times 1008 = 541.935 \; Litre/day$$

$$S_{water\_hot} = \left(\frac{Q_{hot}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_55°C} = \left(\frac{12.9}{15 + 12.9}\right) \times 1008 = 466.065 \; Litre/day$$

From the above, it is clear that, to get hot water of 1008 Litre/day at 40°C, cold water of 541.935 Litre/day at 27.1°C has to be mixed with hot water of 466.065 Litre/day at a temperature of 55°C delivered by the SWHS. From Eq. 7, the solar collector area is estimated as follows:

$$Solar \; Collector \; Area = 2 \times \left(\frac{S_{water\_hot}}{W_{delivery\_SWHS}}\right)$$

$$Solar \; Collector \; Area = 2 \times \left(\frac{466.065}{200}\right) = 4.66065 \sim 4.6 \; Sq.m$$

Solar collector area is found to be around 4.6 Sq. m for capturing the solar energy and convert into useful energy in the form of hot water i.e. 466.065 Litre/day at 55°C.

4.4. Case-IV: 250 litre system delivers 200 litre at 60°C
In Case-IV, if the 250-litre system can deliver hot water of 200 litres per day at 60°C temperatures, then the optimal collector area opted for meeting the user requirement is as follows.
From Eq. 4, cold water to hot water mix is calculated as follows. Now $T_{hot\_water\_SWHS}$ becomes 60°C, $T_{user\_required}$ is 40°C, and $T_{cold\_water\_site}$ is 27.1°C.

$$\frac{Q_{water\_cold}}{Q_{water\_hot}} = \frac{T_{hot\_water\_SWHS} - T_{user\_required}}{T_{user\_required} - T_{cold\_water\_site}}$$

$$\frac{Q_{water\_27.1°C}}{Q_{water\_60°C}} = \frac{60 - 40}{40 - 27.1} = \frac{20}{12.9}$$

From the ratio 20/12.9, the numerator becomes the cold water portion, and the denominator becomes the hot water portion, but to get the individual share in Litre, the following mathematical approach is adopted shown in Eq. 5 for cold water share, and Eq. 6 for hot water share.

$$S_{water\_cold} = \left(\frac{Q_{cold}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_27.1°C} = \left(\frac{20}{20 + 12.9}\right) \times 1008 = 612.766 \ Litre/day$$

$$S_{water\_hot} = \left(\frac{Q_{hot}}{Q_{cold} + Q_{hot}}\right) \times W_t$$

$$S_{water\_60°C} = \left(\frac{12.9}{20 + 12.9}\right) \times 1008 = 395.234 \ Litre/day$$

From the above, it is clear that, to get hot water of 1008 Litre/day at 40°C, cold water of 612.766 Litre/day at 27.1°C has to be mixed with hot water of 395.234 Litre/day at a temperature of 60°C delivered by the SWHS.

From Eq. 7, the solar collector area is estimated as follows:

$$Solar \ Collector \ Area = 2 \times \left(\frac{S_{water\_hot}}{W_{delivery\_SWHS}}\right)$$

$$Solar \ Collector \ Area = 2 \times \left(\frac{395.234}{200}\right) = 3.95234 \sim 4.0 \ Sq. m$$

Solar collector area is found to be around 4.0 Sq. m for capturing the solar energy and convert into useful energy in the form of hot water i.e. 395.234 Litre/day at 60°C.

4.5. Calculated volume of the storage tank
Volume of the storage tank is expressed in cubic meters, and is almost equal to the total amount of water required including the water lost due to heat and leakage losses.

Volume of the storage is calculated using the Eq. 8.

$$Volume \ of \ the \ storage \ tank \ in \ Cubic \ meter = \frac{W_t}{1000} = \frac{W_{r\_site} + W_l}{1000}$$
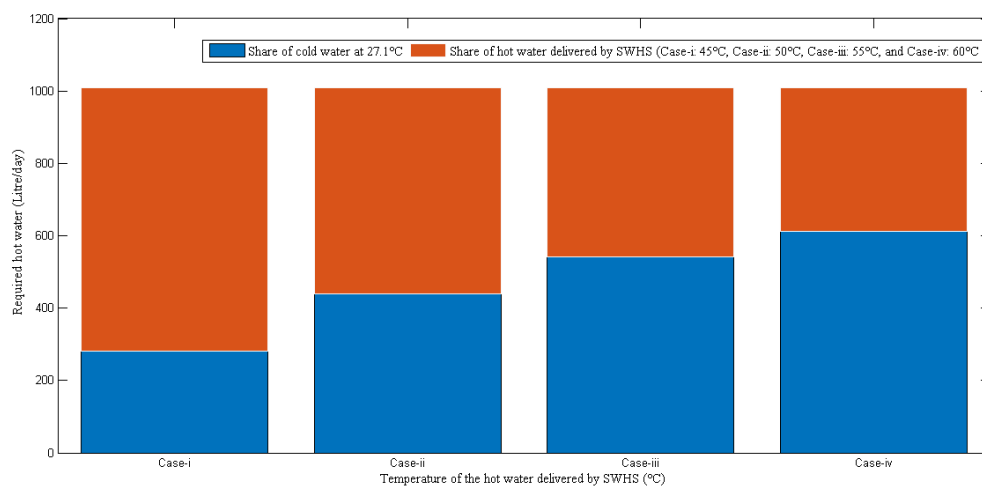
$$Volume \ of \ the \ storage \ tank \ in \ Cubic \ meter = \frac{1008}{1000} = 1.008 \ Cubic \ meter/day$$

4.6. Discussion
Summary of the results is shown in Table 3. Four different cases considered with different temperatures of the water delivery from SWHS (Four different Systems) is analysed and collector area is estimated. As the temperature of the hot water delivered by the system is increased, the share of cold water is increased. This variation is observed due to the fixed temperature that kept as the user requirement i.e. 40°C. Nowadays solar collectors are capable of delivering the hot waters at higher temperatures also, this is because of the advancement in the material used for design of solar collectors.

Table 3. Estimated required solar collector areas.

Parameters	Case-I	Case-II	Case-III	Case-IV
Cold Water Temperature at Site (°C)	27.1	27.1	27.1	27.1
Quantity of Hot Water (Litre/day) at 40°C	1008	1008	1008	1008
Required Hot Water Temperature (°C)	40	40	40	40
Hot Water Temperature at Delivery point of SWHS (°C)	45	50	55	60
Share of Cold Water at 27.1°C	281.564	440.175	541.935	612.766
Share of Hot Water at Defined Temperatures of Each Case	726.436	567.825	466.065	395.234
Solar Collector Area (Sq. m)	7.3	5.7	4.6	4.0

Figure 3. Share of cold water and hot water mix variations.

5. Conclusion

A method for solar collector area estimation is proposed in this work. This method is based on the three different parameters hot water delivery temperatures, cold water temperature at the location, usable temperature. From this study the following conclusions were drawn:

- ➢ As the cold water to hot water mix varies, the required area for the solar collector is also varied.
- ➢ The temperatures of the hot water delivered by the SWHS will also have the influence on the contributions of the hot and cold water mix
- ➢ This method allows the user to estimate the required collector areas effectively and easily. Moreover, it is simple to understand.
- ➢ Hence this would help the owners or the installers to choose the collector's areas as per their requirements.

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