Experimental Investigation of Versa Tyle GRP for Solar Thermal System

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Abstract

Solar thermal systems have encountered a high level of interest over the last ten years due to their low cost and convenience in reducing energy load for domestic hot water. This paper aimed to introduce a new panel's material (Versa Tyle GRP Tiles) for solar thermal system and a prototype was built in a small shed at a site in Liverpool (UK), in order to assess its performance. The experiment was run for 12 months for the purpose of collecting and analysing thermal data in terms of heat capacity, solar energy, and solar fraction. To simulate the daily use of water consumption and provide realistic outputs, the system was emptying every day at different durations in order to investigate the recovery period of the temperatures. The results proved the feasibility and efficiency of the Versa Tyle GRP as the maximum recorded temperature on the tiles was 68^{0}C, and 51 ^{0}C for the hot water in July; while winter months recorded a maximum of 26 ^{0}C for the hot water. The system achieved average solar fraction of 36.52%-47.43% between May to September, while in the rest of the months in the year, average solar fraction of 2.95%-18.59% were detected.

Key words: Buildings, Energy, Climate change, Hot water, Solar system

1. Introduction

Large-scale energy usage has become a major concern due to the increase in demand of energy in the last few decades. Use of conventional energy sources, such as fossil fuels, has brought many environmental problems. Climate change and global warming, the main issues resulting from the release of harmful substances into the atmosphere, have been forcing us to explore alternative energy sources (Reddy et al., 2013; Baharoon, 2015). Solar energy is a free, clean and abundant alternative energy source, it can be utilised by means of solar photovoltaic (PV) and solar thermal systems (Mekhilef et al., 2011). Solar applications are highly affected by weather conditions such as solar radiation intensity, atmospheric temperature, relative humidity and wind speed. It is also affected by a shade that reduces the radiation intensity that reaches the application. This shadow may be caused by dust, clouds, or nearby structures on the application (Kazem et al., 2016; Kazem et al., 2017). Buker et al. (2015) reviewed the solar thermal applications in buildings, they addressed the important issues related to architectural barriers, system design and installation and revealed the trend of solar thermal technologies required in the future.

Many efforts have been carried to assess the solar hotwater system performance using different materials and setup in different locations around the world. For example, Aidah et al., (2018) tested a solar parabolic trough collector system in Iraq, the system captured maximum water temperature achieved in April-2018 was 54°C while the incoming water was 21°C. A study by Xun et al., (2017), investigated solar heating system in an area of Lhasa/China that relatively cold under the simultaneous charging and discharging operation mode using experimental and numerical simulation. It showed that transient coefficient of performance (COP) of the heating system reached an average number of 3.0, which was nearly equal to that of gas-boiler heating system and much higher than that of electrical heating systems. Furthermore, many other researchers (e.g. Hedayatizadeh et al. 2013; Dubey et al., 2014) focused their attention on innovative design changes in order to improve the performance of the solar water heating system. Phase change material (PCM) was used in solar water heaters to store the extra amount of heat energy available during the full sunshine hours, which incorporated thermosiphon solar water. It was shown from the experiments that the PCM improved the performance of the system by bettering stratification number, charging energy efficiency, and thermal efficiency of storage tank (Cabeza et al. 2006; Murali, 2015). Erdemir et al. (2016) investigated the effects of the obstacle types and positions on thermal stratification of a vertical mantled hot water tank by placing four different obstacles inside the tank; these enhanced the thermal stratification compared to an ordinary tank. Too et al. (2009) revealed that the effect of inlet water jets cause forced heat transfer in the mantle gap, so the heat transfer ratio increased with the increase of the water velocity. Arslan and Igci. (2015) and Dehghan et al. (2011) numerically predicted the influence of the operating parameters during discharging mode for a vertical mantled hot water tank. The results indicated that the thermal performance of a domestic solar water thermal storage tank was enhanced by maintaining the tank inflow cold water velocity and inlet/outlet size below a certain limit.

The most communally solar thermal system used is a glazed flat plate collector (FPC) consists of a metal absorber in a flat rectangular casing. A glass cover on the upper surface and insulation at the bottom and sides reduce thermal losses. The annual average efficiency of well designed solar water heating systems (SWHSs) with FPCs in northern temperate climates is typically around 35-40% (German Solar Energy Society, 2007). A number of studies have been carried out on the performance of FPCs under steady-state and quasi-dynamic test conditions following EN 12975-2 (European Standards, 2006). Tiwari et al. (Tiwari et al., 1991) analysed the performance of solar FPCs manufactured in India; it is seen from the results that the values of $F_R U_L$ for the tested collectors ranges from 5.139 to 7.024. It is observed that these values may, however, be improved by using advanced manufacturing techniques, better materials and good bonding methods. Amer, et al.(1998) developed a transient method to characterise the dynamic behaviour of solar FPCs and validated their results against those obtained from steady state tests based on the ASHRAE 93 - 86 standard. Results of dynamic behaviour are very close to those obtained from steady state tests based on the ASHRAE 93-86 standard; the percentage of deviation is about 0.5 and 2.5% in $F(\tau\alpha)_e$ and FU_L, respectively.

Sakhrieh and Al-Ghandoor, (2013) conducted an experimental study to characterise the overall performance of four types of FPCs and an evacuated tube collector used in Jordan. Results showed that the evacuated tube solar collector has the highest efficiency, followed by black and blue-coated solar collectors. The aluminium collector comes in the fourth place. The lowest efficiency is reserved for the copper collector. Despite their lower efficiency, copper and aluminum solar collectors are widely used owing mainly to their lower cost.

This study aims to introduce a new type of active solar collector (Versa Tyle GRP Tiles) using forced convection fluid recirculation for utilizing in different weather conditions for domestic purposes. The innovative system is slightly different from the traditional glazed flat plate (FPC) collector as it made of composite plastic rather than metal absorber as described above. Findings of this study were used to look at how the solar system performs for different months, using an experimental model that was built at a site in Liverpool (UK).

2. Experimental Setup and System Description

A forced circulation solar thermal system (developed by V-solar Ltd) has been installed at the Liverpool John Moores University (LJMU) site in Liverpool at Latitude 53.411815 and longitude -2.98153 (Grid reference: SJ348910). The Liverpool city lies in the North West of England in the UK, is generally characterised with cold weather with annual average high temperature of 13.2 °C and annual average low temperature of 7.2 °C. The experimental system evaluates the thermal performance of technology, which was monitored over a one year period. The test setup consists of the following (see Figures 1 to 3):

- Solar energy collector (Versa Tyle GRP Tiles) with roof area of 2mx2m, tilted with 35^0 and faced to the South
- An interconnecting circuit formed with pipes
- Transmission or heat transfer fluid (water) with antifreeze to avoid the freezing condition in winter
- Hot water storage tank of 110 litres
- Cold water feed
- Pump to flow the water between the collector and the tank
- Flow meter to measure the flow rate through the system: DN15 Single-Jet Hot Water Meter Dry Dial, Maximum Temperature 90°C and accuracy range -1% to +1.2%.

- Thermocouples and probe (temperature sensors): Type K that measures temperature between -35°and +220°C.
- Data Logger (TC-08): Used to record temperature between –270 to +1820°C on computer with the thermocouples plugged to it. TC-08 works with Pico Log data acquisition software that can collect up to 1 million samples. Temperature accuracy Sum of ±0.2% of reading and ±0.5 °C.

Five sensors or thermocouples were placed throughout the system, as seen in Figure 1, to record the temperature over different months (October 2017 - September 2018). The main sensors that were considered in the analysis are on top of the roof panel and inside the storage tank.

The Versa Tyle GRP Tiles (collector) consisted of composite Fibre reinforced plastics (FRP) and glass fibres. It is strong, extremely light and highly versatile and behaves differently to the conventional thermoplastics. The panel has a thickness of 3mm and weight of 2.2kg and was insulated with 30mm thick mineral wool for this experiment. Generally, the Versa Tyle GRP Tiles is used with conventional, pitched, timber roofs, with rafter pitch of 15^0C and over, or hung vertically as a cladding on outer face of external walls.

Typically, solar thermal panels work by transferring heat from the collector to the tank through a separate circuit and a heat exchanger. Heat collected by the panel heats up water that flows through a circuit of pipes into a copper coil inside the hot-water tank. Hot water was drained to mimic domestic hot water use twice a day for different durations: 10, 15 and 20 minutes. System performance data (temperature and flow) were collected every 15 minutes.

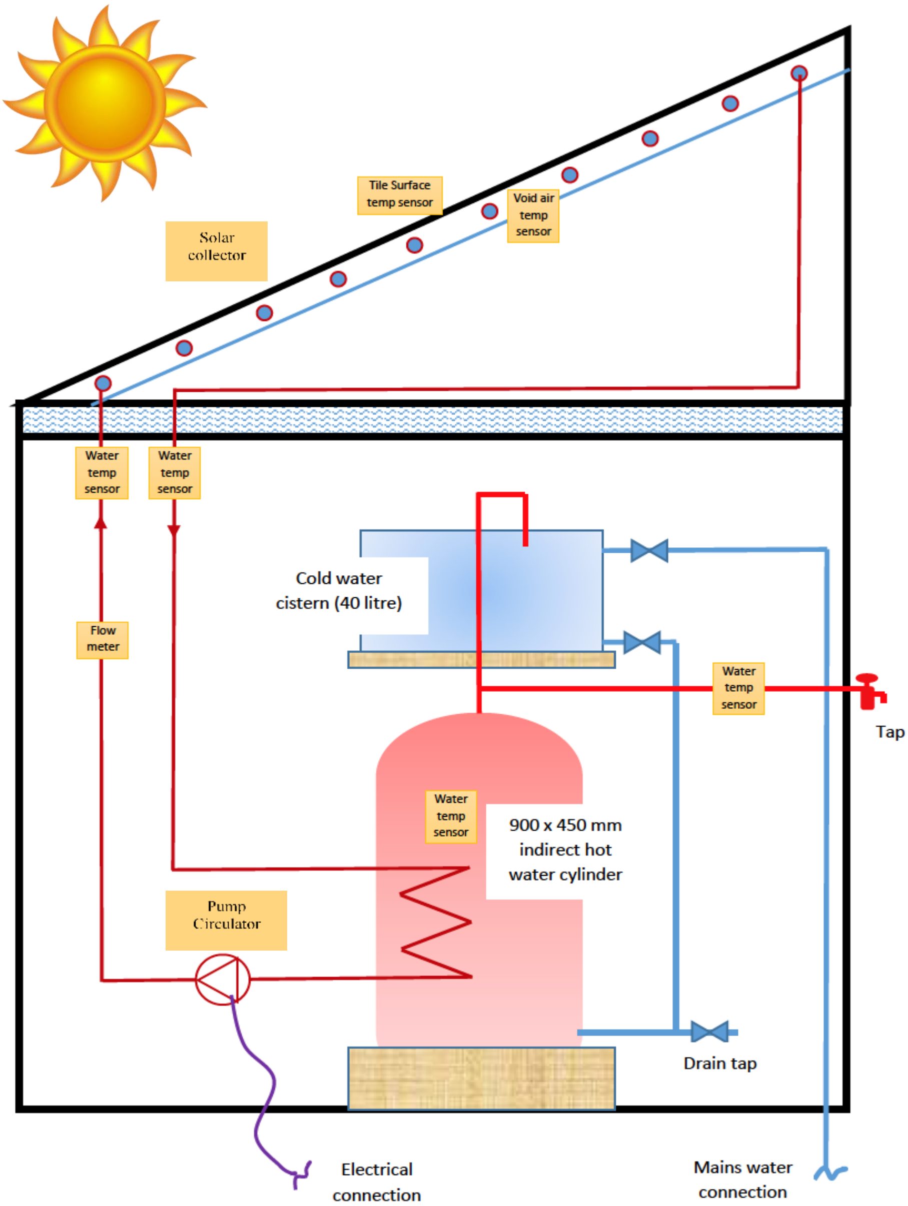


Figure 1: Schematic diagram of the experimental setup

Figure 2: Typical V-solar thermal system at LJMU site

Figure 3: V-Solar system (inside) - the storage tank, measuring equipment and data logger

3. Experimental Approach

Based on the measured temperature and flow rate values of the working fluid at the defined locations (Figure 1), it is possible to gain an understanding of performance of the proposed solar thermal cycle by applying the following equation:

Total heat capacity of the storage tank (KWh) $= \mathrm{m} * C_P * \Delta T$ ……………………………… (1)

Where,

m = Volume of the storage tank in m^3 [110 litres = 0.11 m^3]

C_p = Heat capacity of water [1.16 kWh/m^3K]

ΔT = Difference between hot water temperature of the storage tank and cold water temperature [K]

Based on equation 1, the required heat load for the storage tank to raise the temperature from 10^0C (cold water) to 60^0C (the target temperature) is 6.4KWh.

Once the total energy for daily hot water (DHW) heating system has been calculated, next step will be what proportion of this total the solar system will provide. This proportion is termed the solar fraction and it is the energy supplied by the solar system into the store divided by the total system load. The figure should be stated in association with the relevant target temperature of the DHW, normally 60^0C. At lower target temperatures, the solar fraction becomes artificially higher because not only does the efficiency of the solar collector becomes higher and there are fewer losses in the primary systems, but also the temperature is achieved more regularly.

$$Solar\ fraction(energy\ saving)\% = \left(\frac{\text{Total heat capacity of the tank}}{Total\ heat\ required\ for\ DHW} * 100\right) \quad \text{……………………….. (2)}$$

The collector efficiency was calculated as (Sukhatme, 1998, Duffie and Beckman, 2006):

$$\text{Efficiency}_{\ Collector} = \frac{\dot{m} * C_P * (TC_O - TC_i)}{AG} * 100 \quad \text{………..……………………………………………. (3)}$$

$\dot{m} =$ Fluid mass flow rate (Kg/s)

$Cp =$ Heat capacity of water ($4200 \frac{\mathrm{J}}{\mathrm{kg}}$. K)

$TC_i =$ Temperature of heat transfer fluid entering the collector

$TC_O =$ Temperature of heat transfer fluid leaving the collector (K)

$A = area\ of\ the\ collector, 4m^2$

$G = S$olar radiation falling on collector (W/m^2)

The system efficiency was calculated as (Sukhatme, 1998, Duffie and Beckman, 2006):

$$\text{Efficiency}_{\ System} = \frac{\dot{m} * C_P * (TS_i - TS_O)}{AG} \quad \text{……………………………………………………… (4)}$$

$TS_i =$ Temperature of heat transfer fluid entering the storage tank(K)

$TS_O =$ Temperature of heat transfer fluid leaving the storgae tank (K)

4. Results and Discussion

Global solar radiation on the collector's surface and wind speed data were measured using a weather station consisting of an SMA Sunny Sensor Box equipped with an ambient temperature sensor and an anemometer. The solar radiation sensor had an accuracy of ±8% and a resolution of 1 W/m^2. Typical weather conditions prevalent in the studied site in Liverpool were presented in Figure 4 and 5. Spring and summer were the period with higher solar radiation although there were some continuous days with heavily overcast which have a zero radiation specially for 18-30 June (Figure 4), the maximum daily value was 1038 W/m^2 on the clear sky day of 6th June. Figure 5 shows a plot of wind speed, the chart has the same pattern fluctuating up and down through the year and the maximum wind speed was19 m/s on the day with intermittent cloud cover.

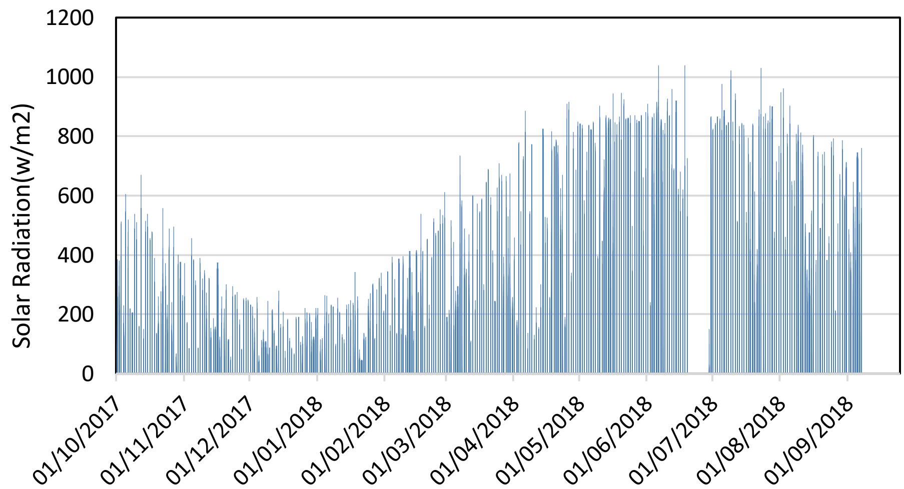


Figure 4. Global solar radiation on the collector surface

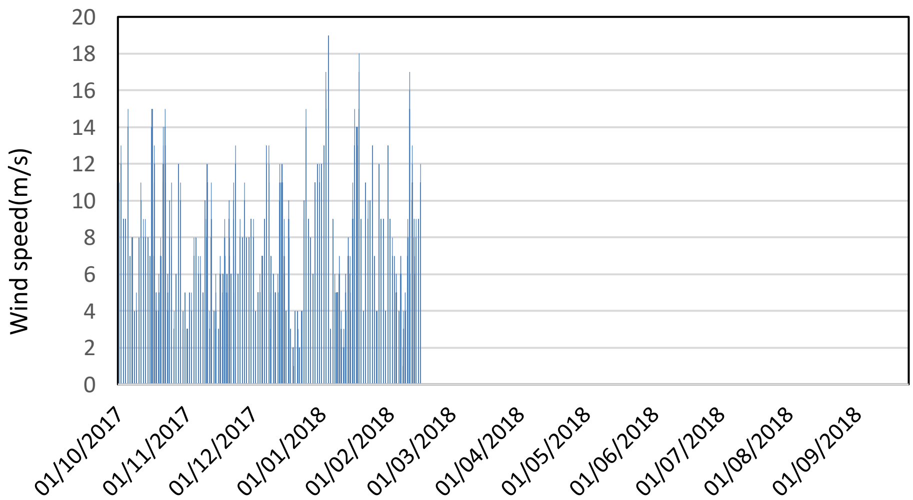


Figure 5. Wind speed in the studied site

The temperatures on the solar thermal panels and storage tank were recorded for each month. Rise in the roof panel temperature causes an increase in storage tank temperature with the same pattern. The maximum recorded temperature on Versa Tyle GRP Tiles was 68.18^{0}C, while the maximum water temperature of the hot water tank was 50.76 ^{0}C (Figures 6&7). Based on the CEBSE guide G (2004), the temperature in the hot water cylinder should not be set below 60^{0}C, as below this temperature bacteria can breed. However, this guide temperature was not reached during the 12 months of running the test (Figures 6&7). As solar energy is an uncontrolled energy source, thus it must be handled with caution. Results showed that the temperature could go below 10^{O}C in the water storage tank, which creates conditions ideal for growth of legionella, or temperatures can be high enough to produce scalding water. Pre-heated water must therefore not be considered as domestic hot water for distribution, until either fully heated by a backup heat source or temperature controlled to prevent scalding, such as by the use of thermostatic blending valves.

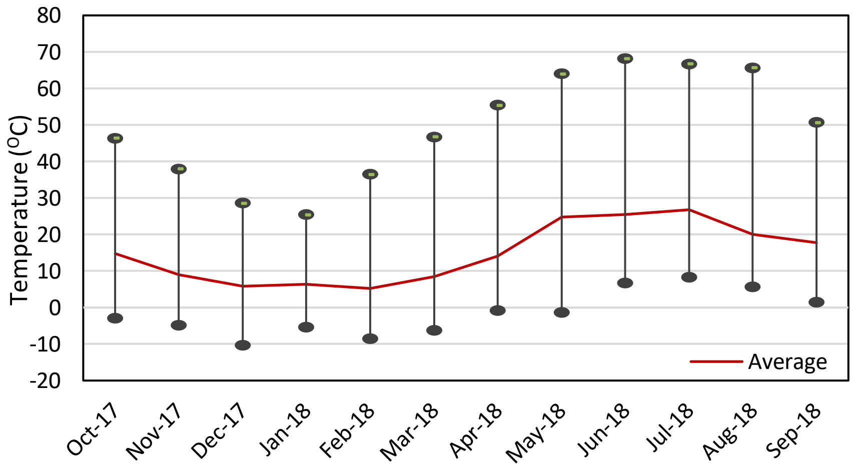


Figure 6: Maximum, average and minimum temperature on the roof panels

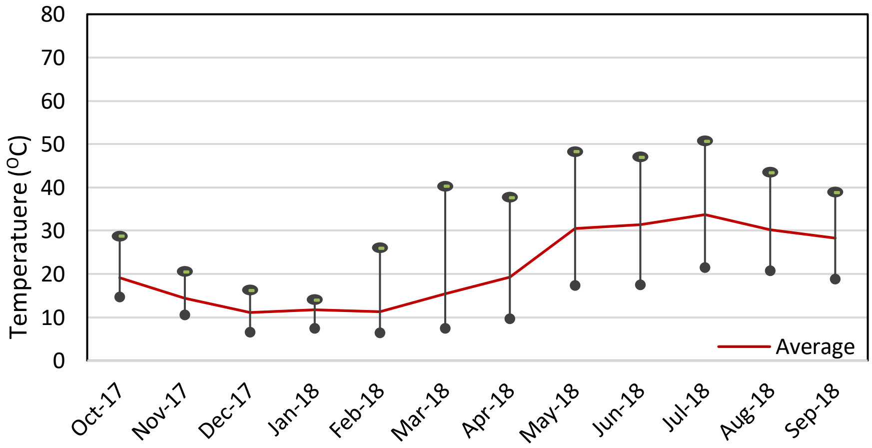


Figure 7 Maximum, average and minimum temperature inside the storage tank

To give more details about the solar system performance, the number of hours for storage water of 40^{0}C, 50^{0}C and above have been assesed and presented in Table 1 and Figure 8. The V-Solar experiment showed that the recommended optimum temprature in the storage tank of 60^{0}C can't be reached with the UK weather. July is the best month, during which, water in the storage tank can maintain 40^{0}C and above for longer period (185.7hours).

In order to get a reasonable assessment of the Solar system and simulate the water use, the system has been emptied twice a day. Figure 9 shows the recovery periods of the temperature for a selected period for each month of the year. The following summarises the recovery process:

- Sometimes the temperature cannot be recovered to the same value when emptying the tank begins; this could be due to low temperature on the solar thermal panels and not enough sun radiation during winter months (e.g. 13th Nov 2017 & 26th February 2017).
- February is the worst month for recovery, as the storage tank temperature remains relatively constant and low at 10^{0}C on average.
- 4th June 2018, the recovery took longer (5hours), because the temperature was fluctuating up and down and that created inconsistency in heating the water, while the temperature of the solar panels for the 27th kept increasing significantly and steadily causing the storage water temperature to recover in a short time (2.5hours).

Table 1: Storage tank temperature of 50^{0}C and above for July with correspondence roof temperature

Date	Time	Roof Temperature (^{0}C)	Storage tank temperature (^{0}C)
02/07/2018	15:04:14	62.24	50.15
02/07/2018	15:19:14	61.02	50.46
02/07/2018	15:34:14	59.55	50.76
Total hours for temperature of 50 ^{O}C and above			00:30

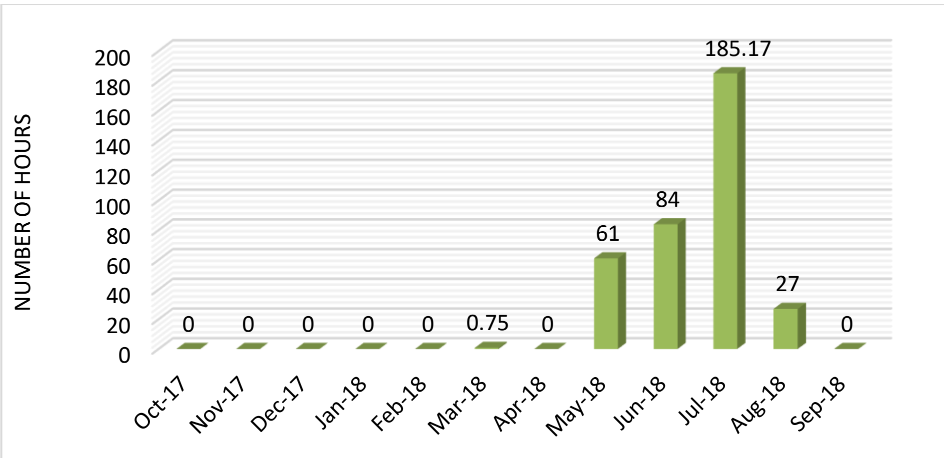
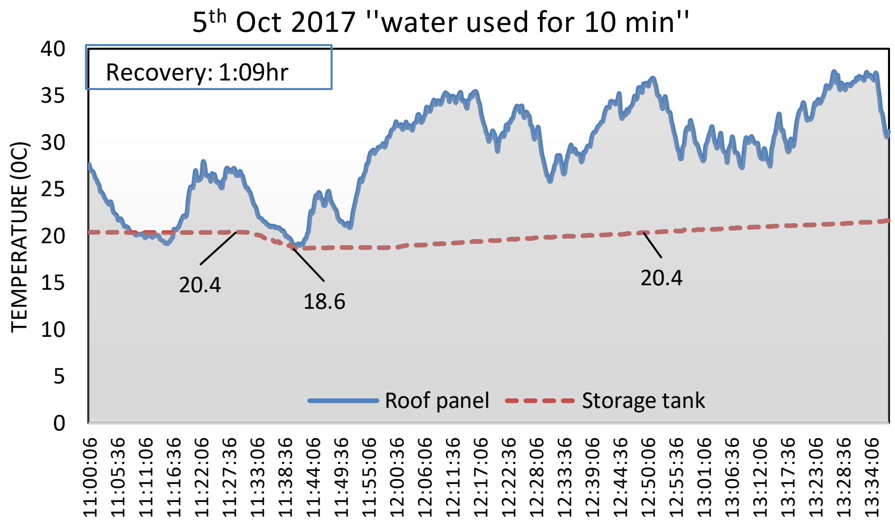
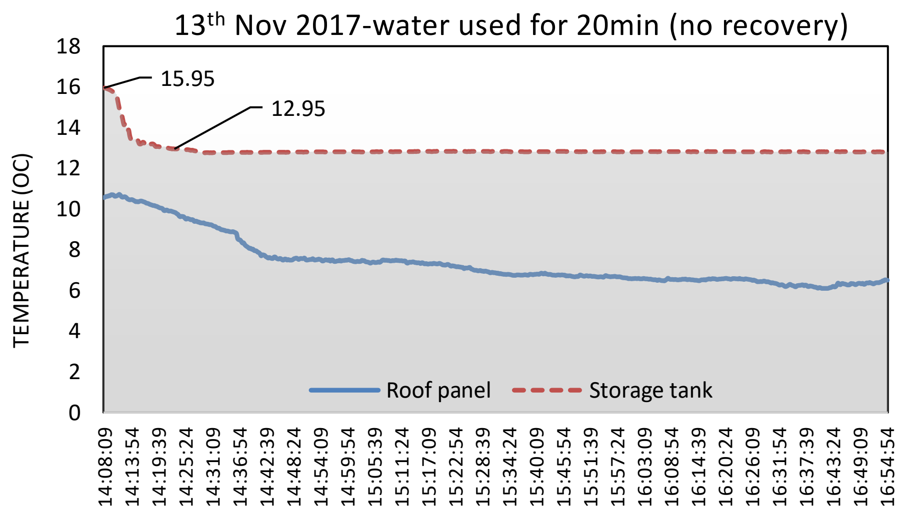
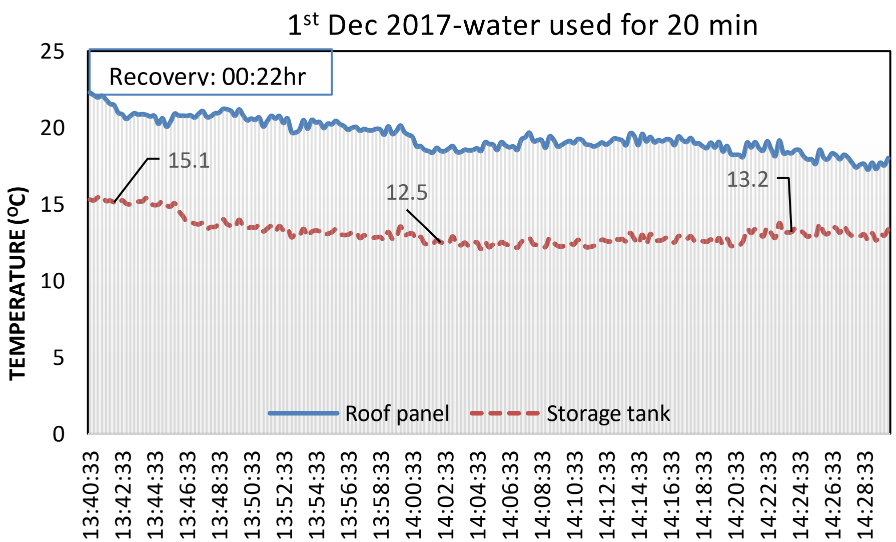
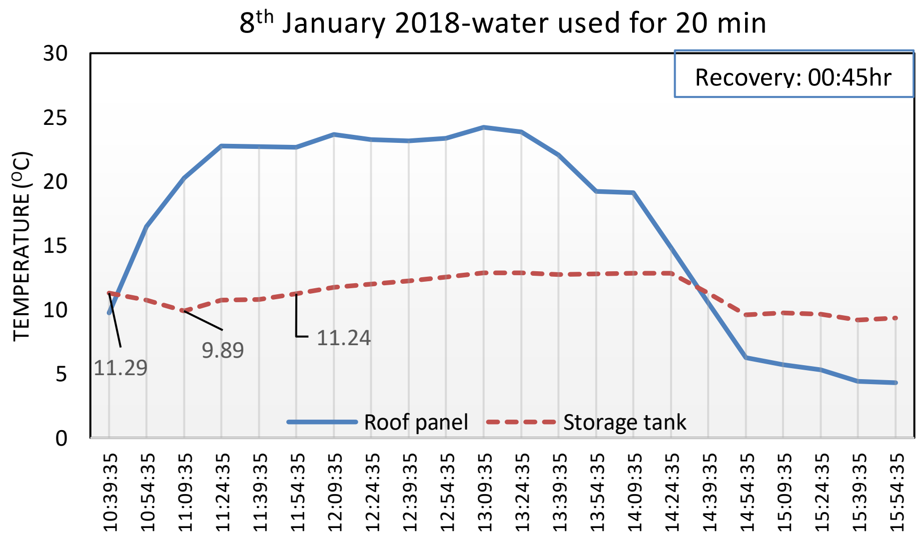


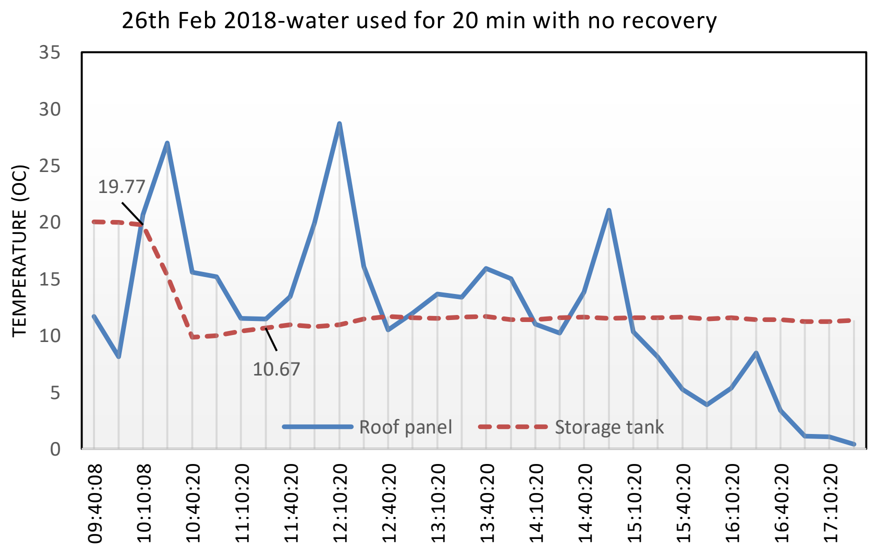
Figure 8: Total number of hours for temprature of 40 ^{0}C and above in the storage tank

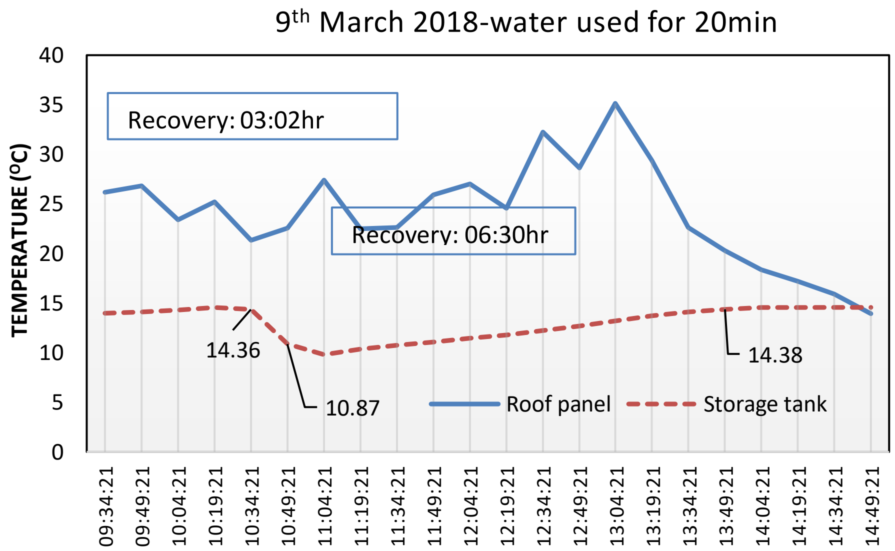

5th Oct 2017 ''water used for 10 min''
Recovery: 1:09hr
TEMPERATURE (0C)
20.4
18.6
20.4
Roof panel
Storage tank

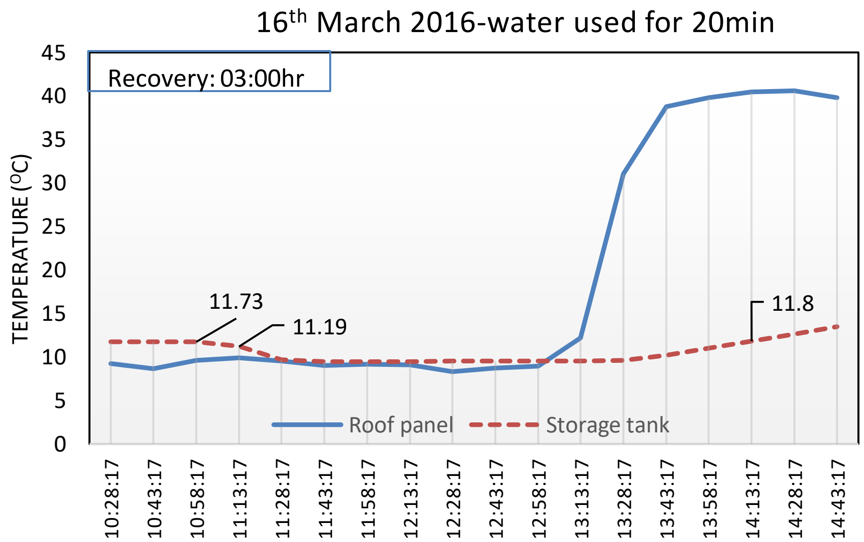

13th Nov 2017-water used for 20min (no recovery)
TEMPERATURE (0C)
15.95
12.95
Roof panel
Storage tank

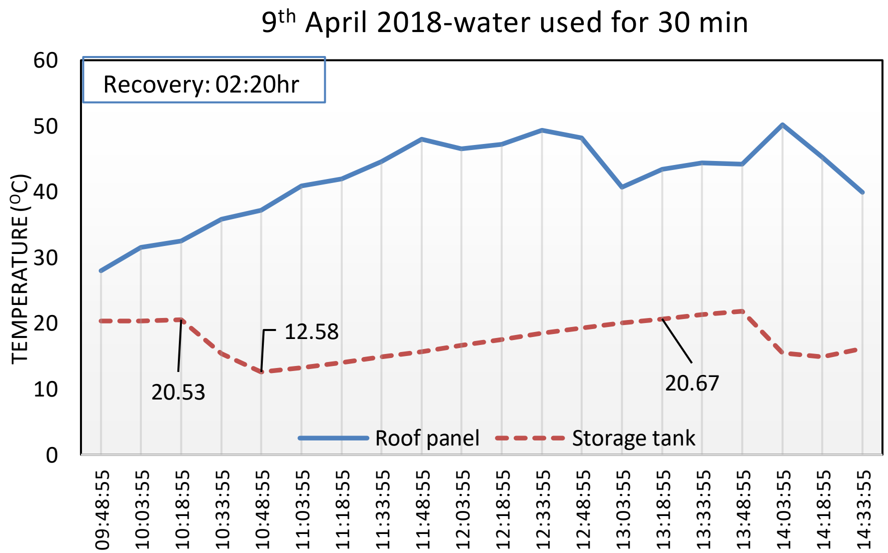

1st Dec 2017-water used for 20 min
Recoverv: 00:22hr
TEMPERATURE (ºC)
15.1
12.5
13.2
Roof panel
Storage tank

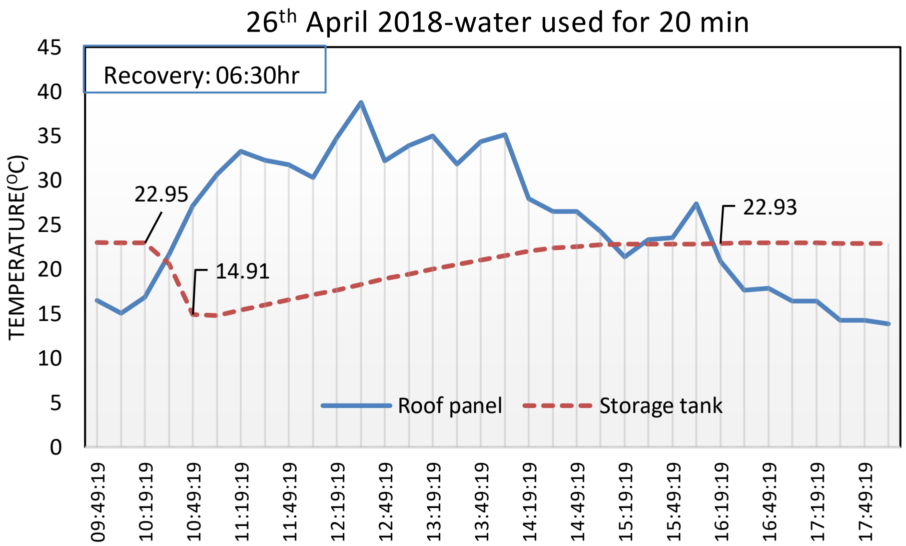

8th January 2018-water used for 20 min
Recovery: 00:45hr
TEMPERATURE (ºC)
11.29
9.89
11.24
Roof panel
Storage tank

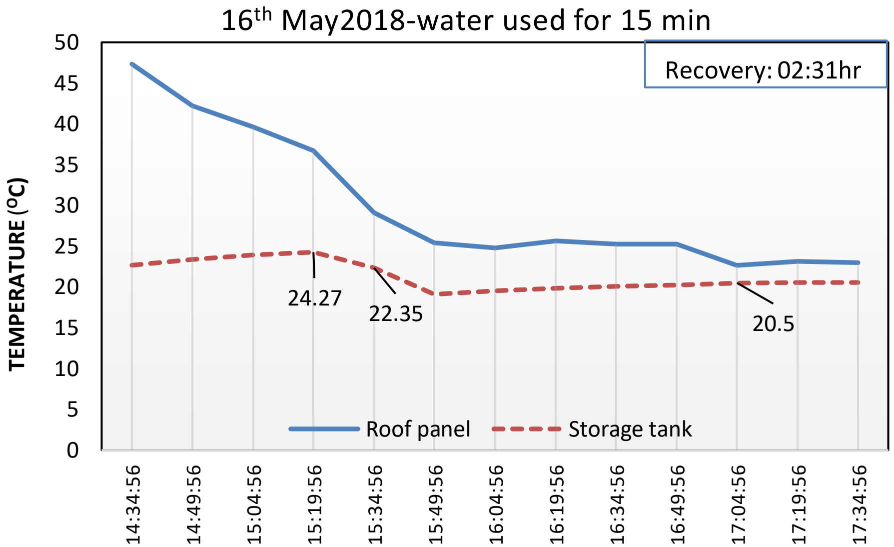

26th Feb 2018-water used for 20 min with no recovery
TEMPERATURE (OC)
19.77
10.67
Roof panel
Storage tank

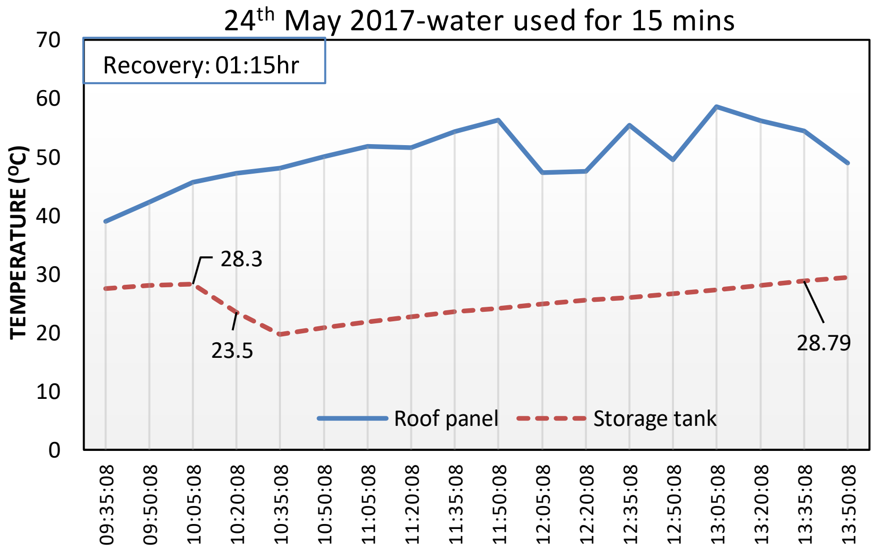

9th March 2018-water used for 20min
TEMPERATURE (°C)
Recovery: 03:02hr
Recovery: 06:30hr
14.36
10.87
14.38
Roof panel
Storage tank

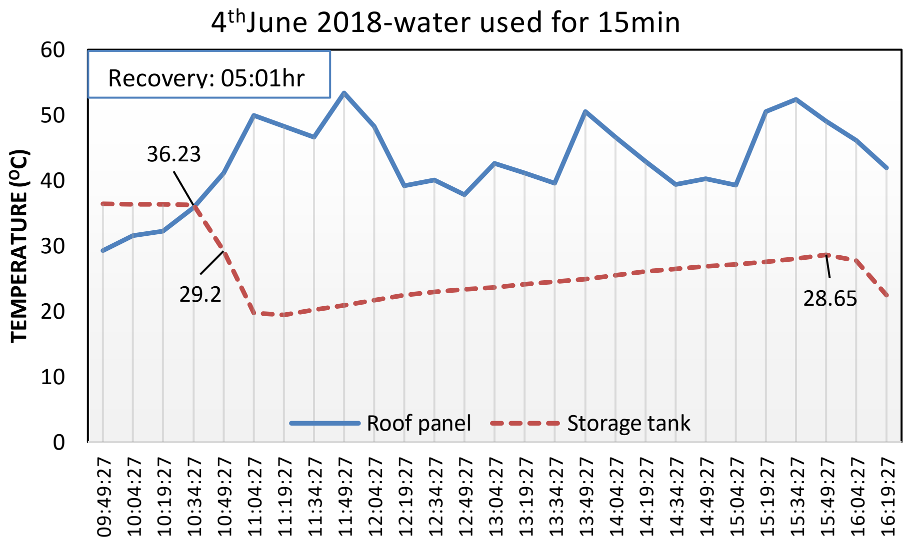

16th March 2016-water used for 20min
TEMPERATURE (°C)
Recovery: 03:00hr
11.73
11.19
11.8
Roof panel
Storage tank


9th April 2018-water used for 30 min
TEMPERATURE (°C)
Recovery: 02:20hr
12.58
20.53
20.67
Roof panel
Storage tank


26th April 2018-water used for 20 min
Recovery: 06:30hr
TEMPERATURE(OC)
22.95
14.91
22.93
Roof panel
Storage tank


16th May2018-water used for 15 min
Recovery: 02:31hr
TEMPERATURE (OC)
24.27
22.35
20.5
Roof panel
Storage tank


24th May 2017-water used for 15 mins
Recovery: 01:15hr
TEMPERATURE (OC)
28.3
23.5
28.79
Roof panel
Storage tank


4thJune 2018-water used for 15min
Recovery: 05:01hr
TEMPERATURE (OC)
36.23
29.2
28.65
Roof panel
Storage tank

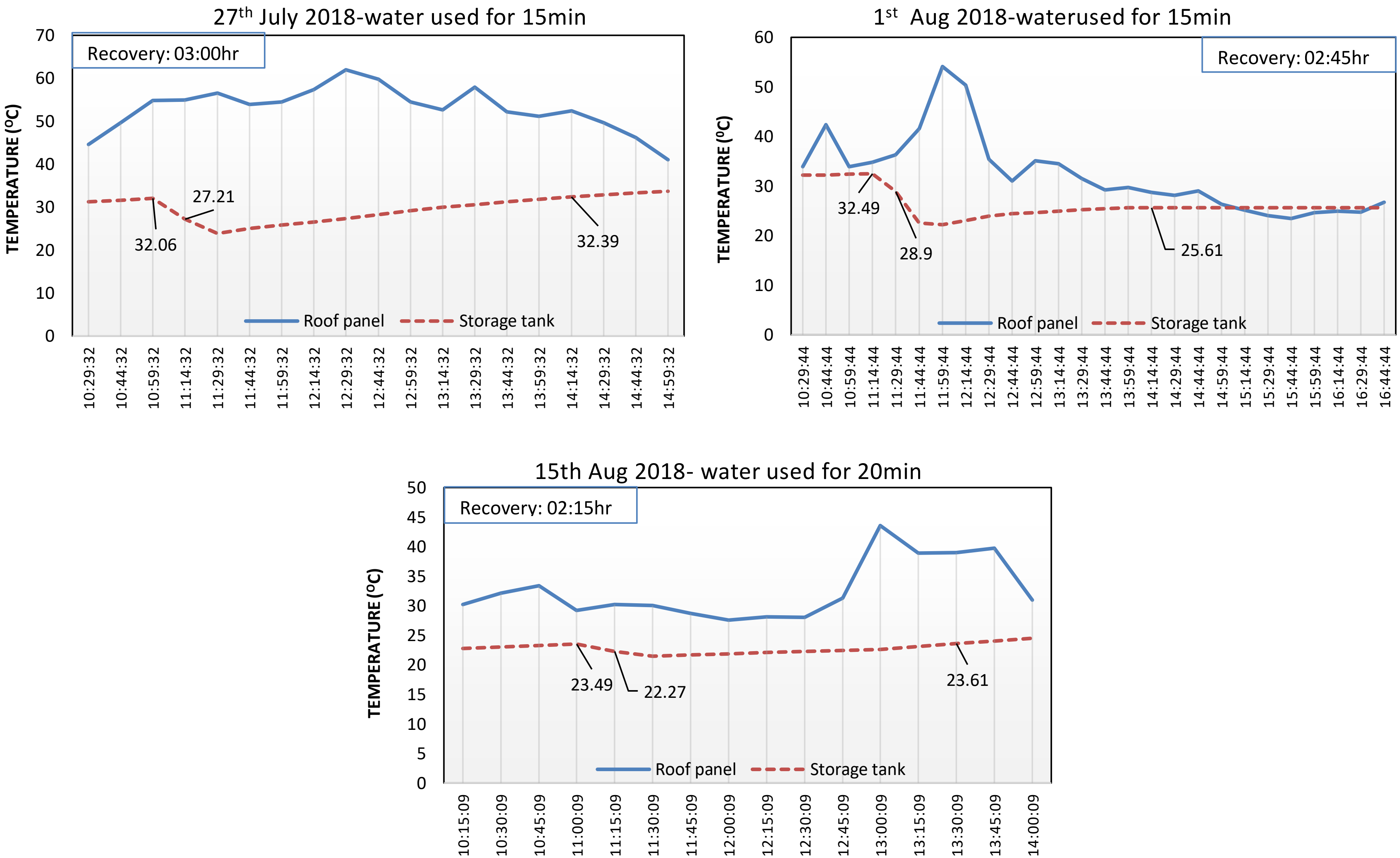


Figure 9: Recovery period for hot water under different durations of emptying the V-Solar system

Useful energy supplied by solar varies throughout different months, as seen in Figure 10. Most of the energy, and hence savings, can be obtained during May to September. In such period, a saving between 2330watts-3030watts can be made, resulting in average solar fraction of 36.52%-47.43% (Figure 11). Apart from the aforementioned period, the rest of the year would have subsequently less monthly solar fraction, ranging between 2.95% and 18.59%. Typical solar fraction figures for the UK vary between 35% and 60% at 60^{0}C (Hammarling and Silk, 2007). This makes the current system's achieved reasonable performance compared with the general standards.

Attempting to increase the annual solar fraction beyond 60% for summer months and up to 100% can results in excess heat being generated during peak sunny days. This requires careful consideration of the system layout to withstand regular stagnation temperatures and potential overheating in store. Figure 11 showed that solar fraction above 60% occurred in May-August; however, these were only for few days.

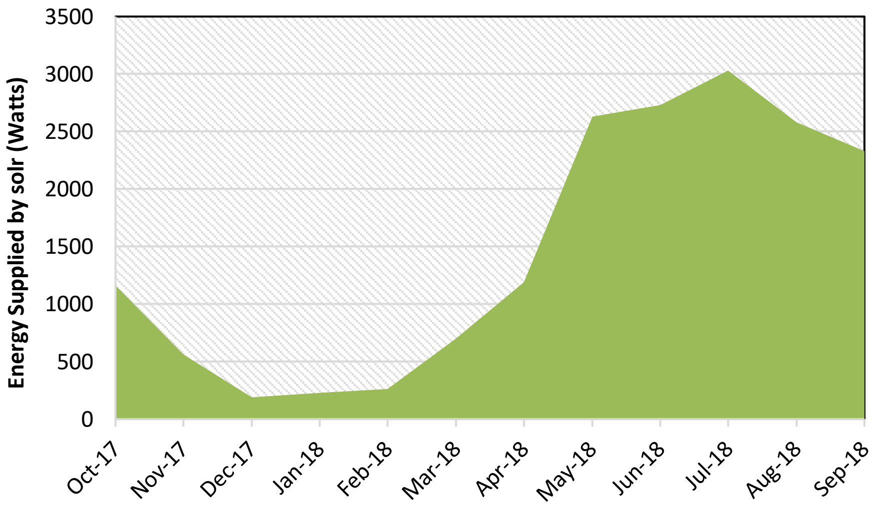


Figure 10: Average monthly solar energy delivered to DHW storage

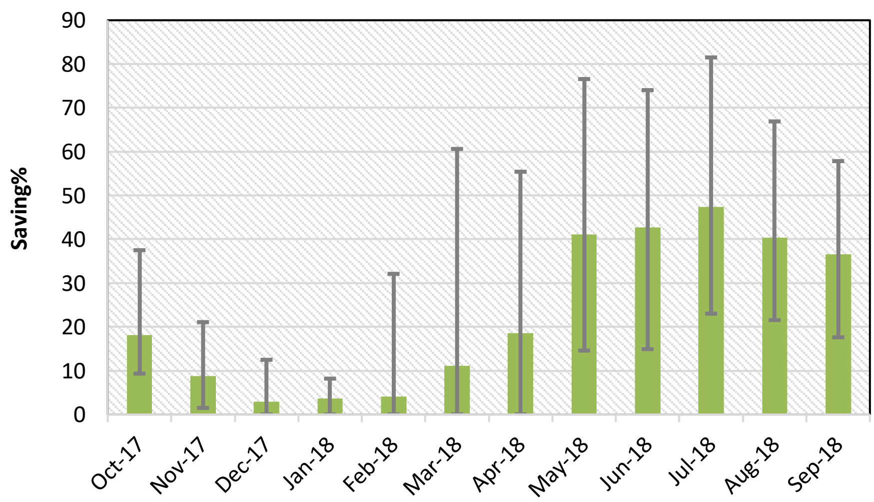


Figure 11: Error bar showing monthly minimum, average and maximum solar fraction

Figure 12 and 13 show the average monthly flow rate through the closed pipe system and the monthly average daily collector and system efficiencies on sunny days. Flow rate was flocculating seasonally and monthly with solar collector temperature and this affected the system efficiencies in Figure 13. The efficiencies varied through the year from 54% in January to 78% in August for the collector while the system varied from 49% in December to 63% in August.

Efficiency of Versa Tyle GRP Tiles has been compared with different collectors as shown in Table 2. It was 7% and 3% higher than the evacuated tube collector (the most common system) that used in Ireland and Poland, which both considered have relatively same environment to Liverpool. While the others in Lebanon and Nigeria showed less performance due to the material of the panel although the system has been tested in arid and semi-arid region.

Uncertainty in the equipment capabilities and performance have also been investigated. The effect of temperature sensor accuracy of ±0.2% for reading (±0.5 °C) and the solar radiation sensor with accuracy of ±8% % has found to have no effect on the solar fraction, useful energy delivered to DHW storage and the system/collector efficiency. This is partly due to the fact that the general accuracy of the equipment is normally of minor effect, however; uncertainty due to numerical simulation is high compared to the experimental testing.

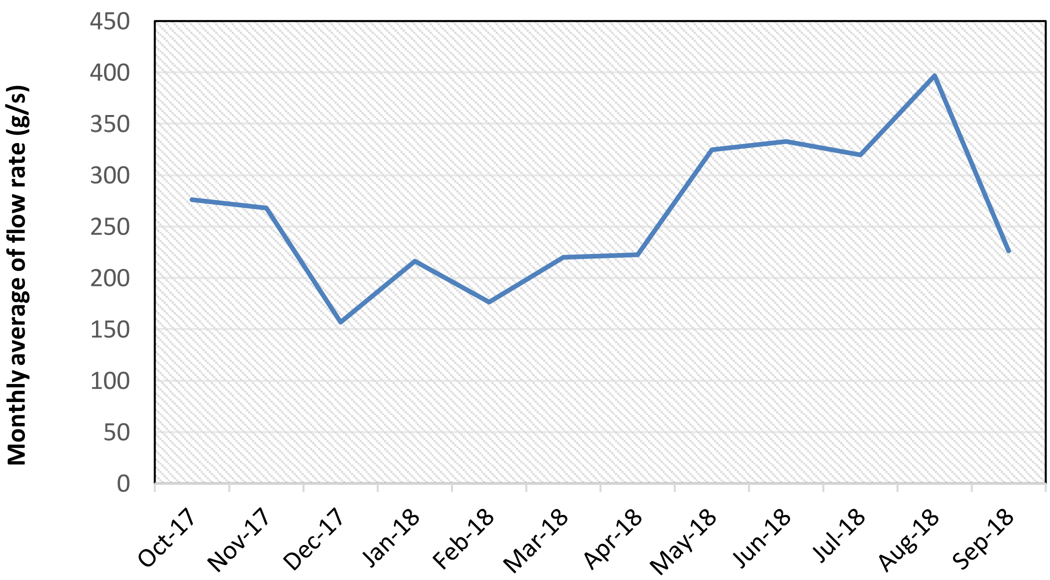


Figure 12: Monthly average flow rate through the closed loop (hot water)

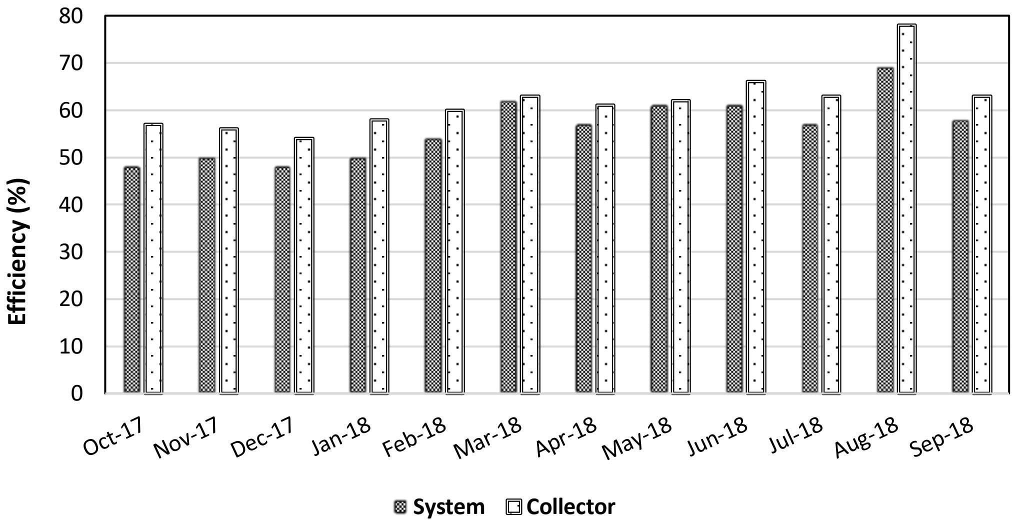


Figure 13: Monthly average daily collector and system efficiencies

Table 2: Comparison of Versa Tyle GRP Tiles with other solar systems in term of average daily collector efficiency

Solar collector type	Other collector	Versa Tyle GRP Tiles
Evacuated tube collector in Ireland (Ayompe and Duffy 2013)	47 to 71%	54%-78%
Evacuated solar collector in Poland (Siuta-Olcha1 et al., 2020)	11 to 75%	
Water-in-glass collectors Lebanon (Hayek et al. 2011)	15 to 20%	
Hermosyphon collector coupled with FRP storage tank in Nigeria (Nwosu et al., 2011)	35 to 40%	

5. Conclusions

This study showed that Versa Tyle GRP Tiles used for solar thermal systems are a very interesting solution to reduce the environmental impacts of domestic hot water production. The solar experiment that was conducted in a site in Liverpool, UK reflected that a maximum saving of up to 3kW could be reached in the period May to September, with a lower solar fraction during the rest of the year. Whilst it is possible to ‘’oversize a collector’’ to gain greater coverage in spring and autumn, this can present overheating problems in summer and reduce cost effectiveness. The energy efficiency of Versa Tyle GRP Tiles system was strongly related to the intensity of solar radiation. As indicated by the calculation results of the system efficiency was equal to 61% in the warmer months (April to September) and 52% during the colder months (period from October to March). Versa Tyle GRP Tiles collector showed also higher performance when comparing their daily efficiency (54 to 78%) to the most efficient collector evacuated tube collector (11 to 75%) in a similar environment to Liverpool. This merely due to high material conductivity in absorbing more solar radiation than the evacuated tube.

To summarize, it can be concluded that only about 1/3 of the solar energy that falls on the solar panels has been converted into useful heat supplied to the domestic hot water system. So, this level of energy efficiency can be applied to any type of economic evaluations associated with the use of solar collectors for water heating in similar types of buildings in areas with a similar climate to Liverpool. It is recommended that the system should be tested in a typical domestic hot water system, taking into consideration the occupancy level and consumption profile during the day throughout the year. Moreover, it is recommended to use advanced special/efficient coatings on the absorber surface of the collector assist the efficiency by reducing the "re-emittance". This will reduce the loss of energy re-radiated back out of the panels, hence improving the overall transfer of the solar radiation.

Acknowledgments

This study was conducted as part of a research project (Low Carbon Eco-Innovatory) in Liverpool John Moores University-UK to test a new solar thermal systems. The authors, in particular, would like to acknowledge the financial support rendered by the European Regional Development Fund 2014-2020 (ERDF, 22R16P00567 (22R15P00045)), special thanks are due to V-Solar Ltd for their cooperation.

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