Pump Speed Optimisation for Solar Thermal System

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***Abstract*—Photovoltaic as well as solar thermal systems have been particularly useful for harvesting the inexhaustible energy from the sun and to reduce the carbon emissions normally produced by burning fossil fuels. In either of these cases, reaching a higher efficiency obviously brings substantial benefits, and while much research has been performed on PV efficiency, most research has focused on the solar thermal collectors themselves, while our approach considers the system's perspective by optimizing the pump speed based on the performance of the various heat exchangers within the full system. In order to test the theory, a prototype solar thermal system was built, in which the pump speed was adjusted by considering: the water demand, the input and output temperatures of the solar panel and the output temperature of the produced hot water. By combining the solar thermal system with an existing gas boiler and continuously adjusting the pump speed, a reduction of between 10 to 30% in gas consumption and 5 to 10% in electricity consumption was observed.**

INTRODUCTION

Due to the ever-increasing global population and an increased integration of technology, as demonstrated by the link between growth of the GNP per capita [2], the world's energy demand will most likely continue to grow and so the use of renewable energy sources is of significant importance. Normally, renewable energy is generated from either hydro, wind or solar sources.

Out of these three sources, solar energy is used within this study. Solar energy harvesting can be achieved by using Photo-Voltaic (PV) electrical systems or Solar Thermal systems. While the latter have been designed to gather the sun's radiation energy and use it to heat water or any other liquid, for industrial, commercial and/or domestic use. Either of these systems can be hugely profitable, depending on the user demands and installation, and their installation helps to gradually decrease the quantity of site-related greenhouse gases like: Carbon dioxide (CO_2), Methane (CH4), Nitrous Oxide (N_2O), Ozone (O3) and water vapour that are all associated with the use of conventional, fossil-based sources [1].

While solar thermal systems were invented in the early 1890s in California and commercially approved in the late 1970s, it took until the 1980s for these systems to commercialise. As the current technology is quite mature and therefore overall cost-effective, efficient and well regulated, it has been adopted in many infrastructures to aid with the need for hot water. However, limited work has been performed on efficiently integrating and combining these systems with existing installations, which is the focus of this paper.

This paper starts of by looking at the theoretical aspects of such an integration, which is then followed by representing an extensive set of data gathered on the real system, after which the paper concludes.

THEORETICAL STUDY

For a solar thermal collector, the heat exchange within the panel is essential to its efficiency and has been studied for various designs [4, 5].

However, the overall system has a second heat exchanger, within the storage tank, which could have a quite different characteristic from the collector itself. This implies that the pump speed as optimal for the collector may be different from that for the storage tank, which means that compromises may need to be made in reaching an optimal overall efficiency. In order to achieve such optimization, a variety of points within the system need to be measured and a suitable controlling algorithm derived that combines the information of these sensors into an optimised pump speed. This research project involves designing such a controller for use on a domestic hot water system which was adapted for this study. In order to better appreciate the complexity of combining different heat exchangers and their characteristic, rather than obtaining an off the shelf solar thermal panel, a collector was built from scratch following the guidelines presented in [6, 7].

The fully installed system, as shown in Figure 1, consists of two circuits. The first circuit, is a closed circuit and comprises of the solar thermal panel, a circulating pump, a flow meter (FRSP), an expansion vessel and a heat exchanger as part of the heat storage vessel. The second system, is an open circuit and consists of the same heat exchanger/storage vessel, a flow meter (FRHW), and an expansion vessel. Normally Open/Normally Closed (NO/NC) electro valves are fitted on both circuits to allow the normal operation of the system and to control the safety system of the circuit. If in normal operation a valve has to stay open, a NO valve was chosen and vice versa. In this way, the valves will need to be powered up only for emergency. The closed circuit uses antifreeze fluid, because the pipe work goes through the solar thermal panel located on a roof in the UK, and could therefore experience freezing temperatures. Using antifreeze liquid also aids with the heat conduction and exchange as well as helping to prevent pipe oxidation. As the antifreeze fluid is heated up by the sun and gains thermal energy, this energy is transferred to the water in the storage's heat exchanger. To minimise heat losses, this heat exchanger is positioned within the loft, immediately under the solar panel, while all pipes are insulated.

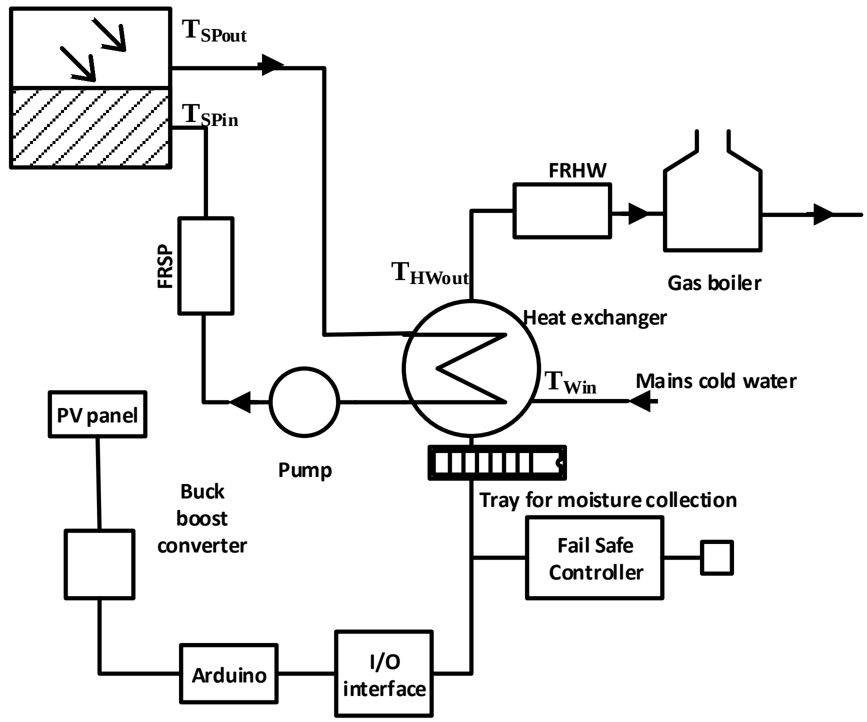

Figure. 1 Block diagram of the solar hot water system

Throughout the system there are various points of data collection, which are: the temperatures at the solar panel inlet (T_{SPin}), the solar panel outlet (T_{SPout}), the hot water circuit inlet (T_{HWin}), and the heat exchanger outlet (T_{HWout}), while the flow rates in the closed (Flow Rate Solar Panel, FRSP) and open circuit (Flow Rate Hot Water, FRHW) are measured as well as the solar Illumination (Ill). The latter is measured through a small PV panel, which also powers the electrical part of the installation.

All of these measured parameters form the input to the controller, which uses them to continuously adjust the optimal pump speed. In order to determine this pump speed, each measured parameter is multiplied by a specific value, which allows one to optimise the pump speed for a variety of different usage and other environmental conditions, resulting in the following formula:

$$pumpspeed = FRHW * K_f - \Delta T_{HW} * K_{HW} + \Delta T_{SP} * K_{SP} + \Delta T * K_{\Delta T} \ (\%) \quad (1)$$

The four 'K' values are the respective "multipliers" to adjust the influence of that respective factor. By changing these values, the pump speed and the circulating fluid flow vary, based on the efficiency of the heat transfer. The 'K'-values have the following meaning and are calculated as follows:

- K_f - is calculated by considering the maximum PWM output for a 10-bit micro-controller, divided by the maximum flow rate of the system's pump.

$$K_f = X \frac{PWM_{max}}{flowrate_{max}} = X \frac{1023}{20} \quad (2)$$

- K_{HW} - is determined by considering the maximum and minimum temperatures of the heated water.

$$K_{HW} = Y \frac{PWM_{max}}{T_{HWmax} - T_{HWmin}} = Y \frac{1023}{65-12} \quad (3)$$

- K_{SP} - is calculated by using the maximum and minimum temperatures of the fluid at the in- and outlet of the solar panel.

$$K_{SP} = Y \frac{PWM_{max}}{T_{SPmax} - T_{SPmin}} = Y \frac{1023}{80-12} \quad (4)$$

- $K_{\Delta T}$ - considers the maximum values of the outlet temperatures of the solar panel and the hot water system.

$$K_{\Delta T} = Y \frac{PWM_{max}}{T_{SPmax} - T_{HWmax}} = Y \frac{1023}{80-65} \quad (5)$$

Within the above formula, the values 'X' and 'Y' dictate how much the constant 'K' weighs within the whole formula. X as well as Y can have a value between 0-100, and affect the pump speed and consequently influence the heat exchanger efficiency. For the purpose of this work, two different values were chosen, namely X=80 & Y=20 and X=60 & Y=40. This results in the following respective 'K'-values: K_f = 40.92, K_{HW} = 3.86, K_{SP} = 3.00 and $K_{\Delta T}$ = 29.23 or K_f = 30.69, K_{HW} = 7.72, K_{SP} = 6.02 and $K_{\Delta T}$ = 27.28.

When the house needs no hot water, then the circulation of the water in the close circuit only aids when it can increase the temperature of the storage tank. However, when hot water is demanded, then there will be cold water flowing into the storage/heat-exchanger tank, which needs to be heated up, and this requires the liquid in the closed circuit to start circulating more regularly, which is the main reason for the fact that the X-value is much higher than the Y-value.

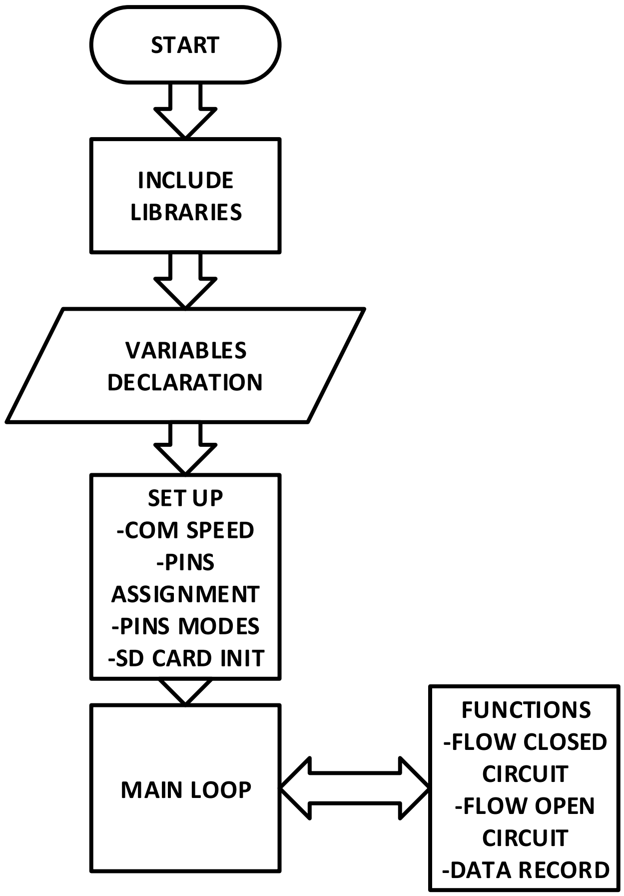

Figure. 2 Flow Chart Diagram

With the calculated 'K' coefficients, the first parameter of the equation has an influence of 80% or 60% of the total speed adjustment while the second, the third and the forth parameters were set at 20% or 40% in Equation 1. It is worth nothing that since one of the factors is negative, the total reaches 100% in either case.

The equation's second parameter slows down the pump based on the fact that if the temperature of the storage's heat exchanger has reached its optimal (65°C) then the only purpose is to keep the water at this temperature, while preventing the heat to escape to the outside (when the outside temperature could be lower), that is why it is subtracted in the formula.

When the solar panel temperature is higher, then there is also a higher benefit in increasing the pump speed as influenced by the third parameter, which checks the temperature difference on the solar panel ΔT_{SP}. Finally, the last parameter considers the difference in temperature between the fluid coming out of the solar panel and the hot water coming out of the heat exchanger. The larger this temperature differential, the higher the pump speed should be in order to heat up the water in the storage tank. When the temperature difference is negative, then the pump stops working because that means that the storage tank's water is at a higher temperature than the solar panel's fluid.

In practice, the sensors were all linked up to an Arduino board that drives the pump by adjusting its PWM continuously. Figure 2 shows this process of using a closed control loop to control the system. Additionally, interrupts were added to read the flow values in both circuits and to record all measured data onto an SD card.

The controller and other electronic components are all fed of a small photovoltaic panel that is combined with a backup battery. This panel is also use to measure the solar illumination information, which is an input to the system, available for future optimisations.

Due to the fact that the full system is located in the loft, any leakage could have massive consequences, and therefore a protection circuit is also implemented, as detailed in Figure 3. The aim of this system is to deal with situations such as an overheating heat exchanger or any potential leaks around the heat exchanger itself.

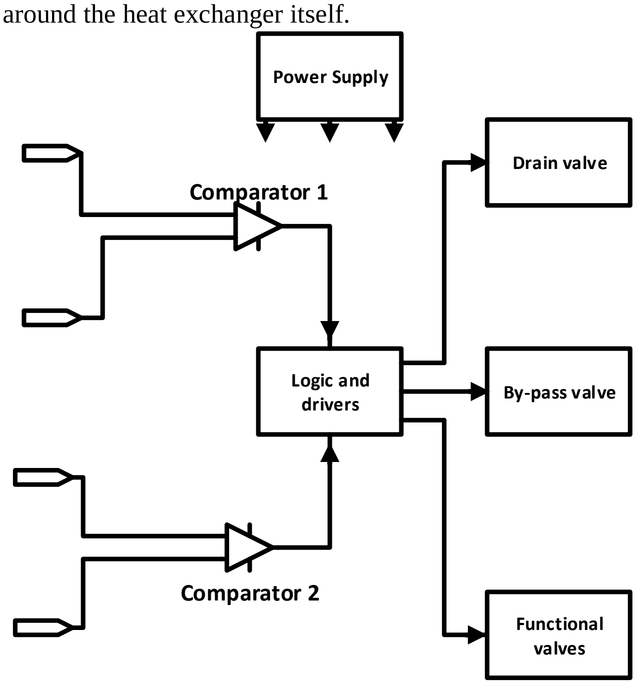

Figure. 3 Fail Safe System

To deal with the changes in pressure when water heats up, two expansion vessels are fitted, one in the closed circuit and one in the hot water, open circuit. Additionally, the protection circuit consists of two temperature sensors, one at the hot water output pipe and one on the outside shell of the heat exchanger. This temperature information is combined with that of two dew sensors mounted in a tray underneath the heat exchanger in order to pick up potential leaking into the tray.

The actual protection board uses an LM339 quadruple comparator, which senses the differences between the output voltages given by the four sensors and the reference voltages determined during the calibration of these sensors.

The output of this comparator is then linked with a set of MOSFETs that drive various electro valves which help to drain the water from the system in case of a detected emergency. The safety circuit has its own separate power supply, in line with assuring full system redundancy.

RESULTS AND DISCUSSION

As the system continuously logs its data, and has been running for over a year now, there is a large data set to pull from, however, the challenge lies in testing different parameter settings, as there are so many environmental factors that influence the outcome and change continuously.

The presented results were recorded during different seasons of the year, and different 'K' values were used to adjust the pump speed, based on the previously presented X and Y values.

Figure 4 shows data for two days in January 2017 with the coefficient K_f set at 80% and coefficients K_{SP}, K_{HW} and $K_{\Delta T}$ set at 20%, while Figure 5 shows data for two days in July 2017 with the same K-value settings. In each case, the 'X' axis represents time and the 'Y' axis shows the measured value, where the value of the illumination has been reduced by a factor of 20 times to not suppress the other values.

From Figure 4 & 5 one can observe that the pump speed is continuously adjusted during the day, at night it stops due to the outside temperature being lower than that of the water in the tank. One can also note a quite typical demand for hot water in the morning and evening during the summer period, while there is a more continuous demand over the winter, due to the needed space heating.

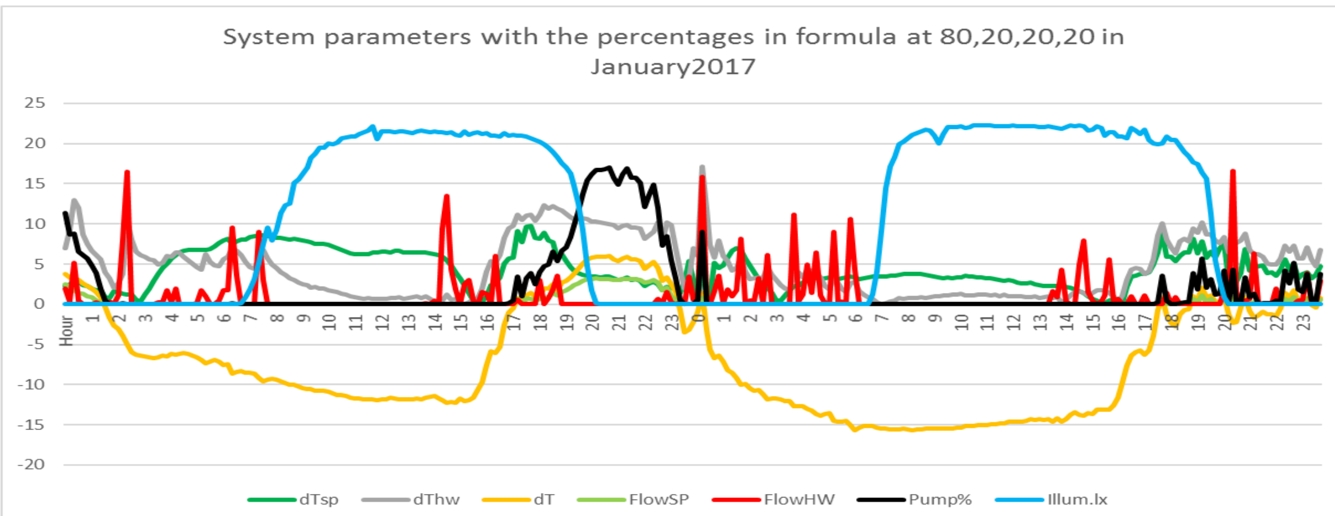

Figure. 4 Data log 6th-7th of January 2017

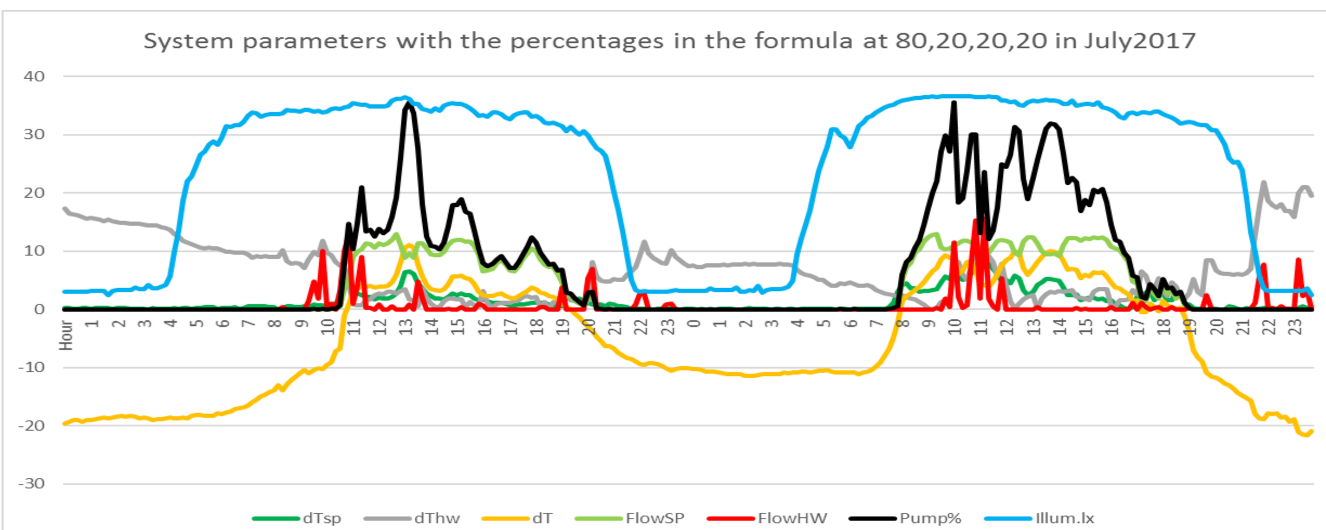

Figure. 5 Data log 1st-2nd of July 2017

Additionally, the amount of heat that can be harvested over the summer is also significantly higher than that available during the winter months. In the latter case, the heat comes "available" much later in the day and is of much lower value.

However, by combining demand with the tank's temperature and the thermal input to the solar panel adjusting the pump speed seems to allow for an optimised energy harvesting.

As the coefficients K_f, K_{SP}, K_{HW}, and $K_{\Delta T}$ are changed to 60, 40, 40, and 40 respectively, one can notice that the pump speed is much less influenced by the demand, while the temperatures of solar panel, hot water and the temperature difference is much more important in changing the pump speed. However, one should note that the use of the system largely depends on demand, and so a more demand driven operation, is more suitable. This stands in contrast with the more standard installations of these systems, where the pump speed would be running at a fixed speed, continuously.
Figure 7 shows data for the pump running at a fixed speed. This then means that there is a constant flow within the solar panel. This results in a depletion of the heat stored within the tank during the night, which is obviously not wanted, so a start/stop functionality is the minimal requirement for a solar thermal installation. This approach obviously also consumes more energy, as the pump runs continuously at full power, while the energy harvested is not optimised towards the demand.

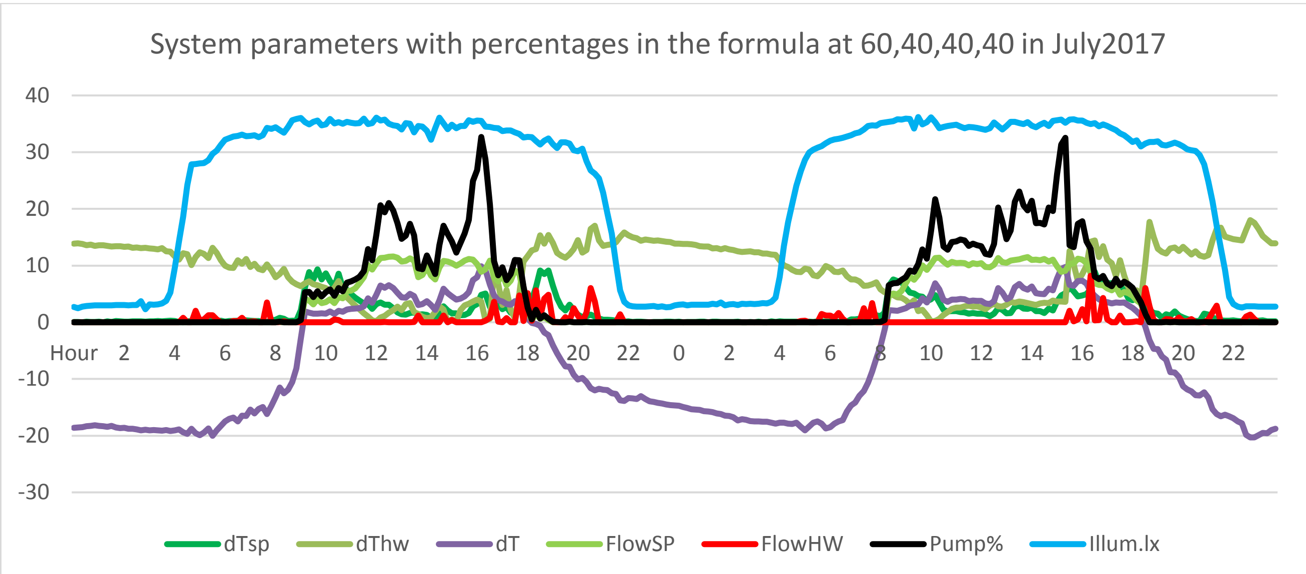

Figure. 6 Data log 3rd and 4th of July 2017

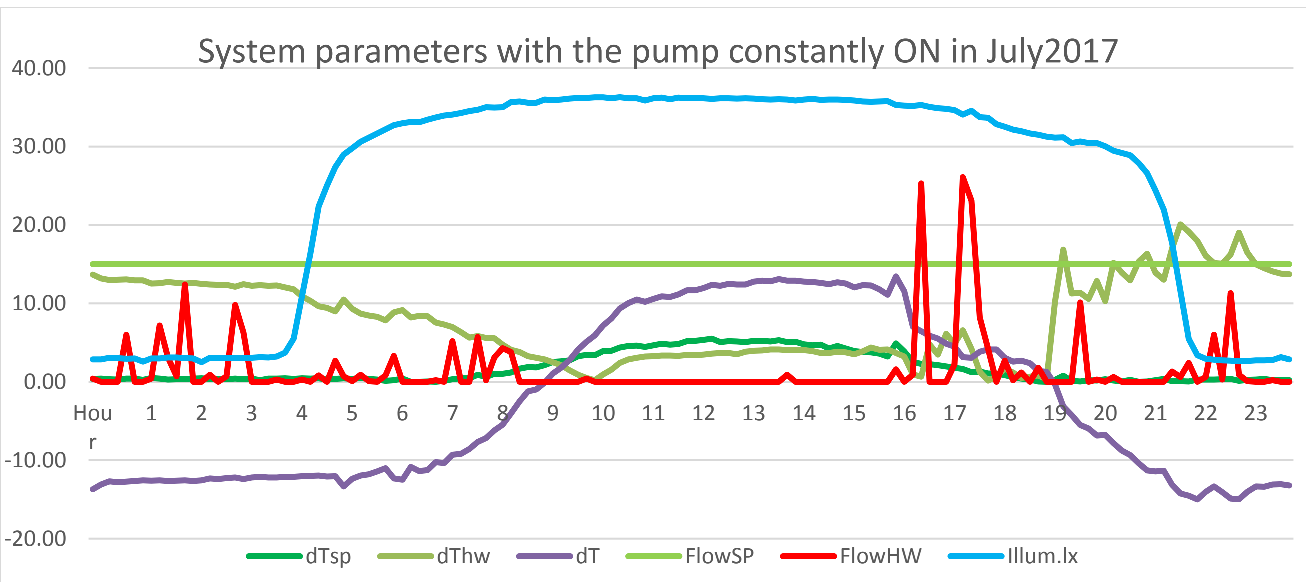

Figure. 7 Data log fixed pump speed on the 5th of July 2017

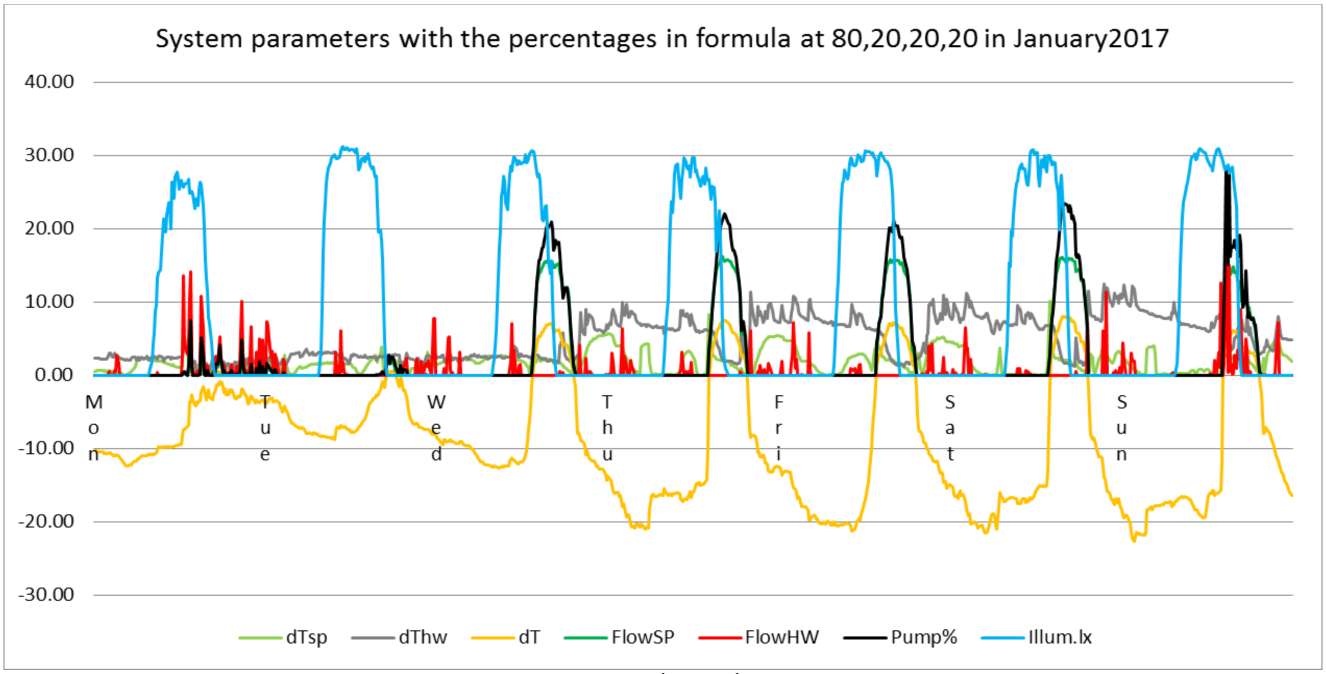

Figure. 8 Data log 9th to 15th of January 2017

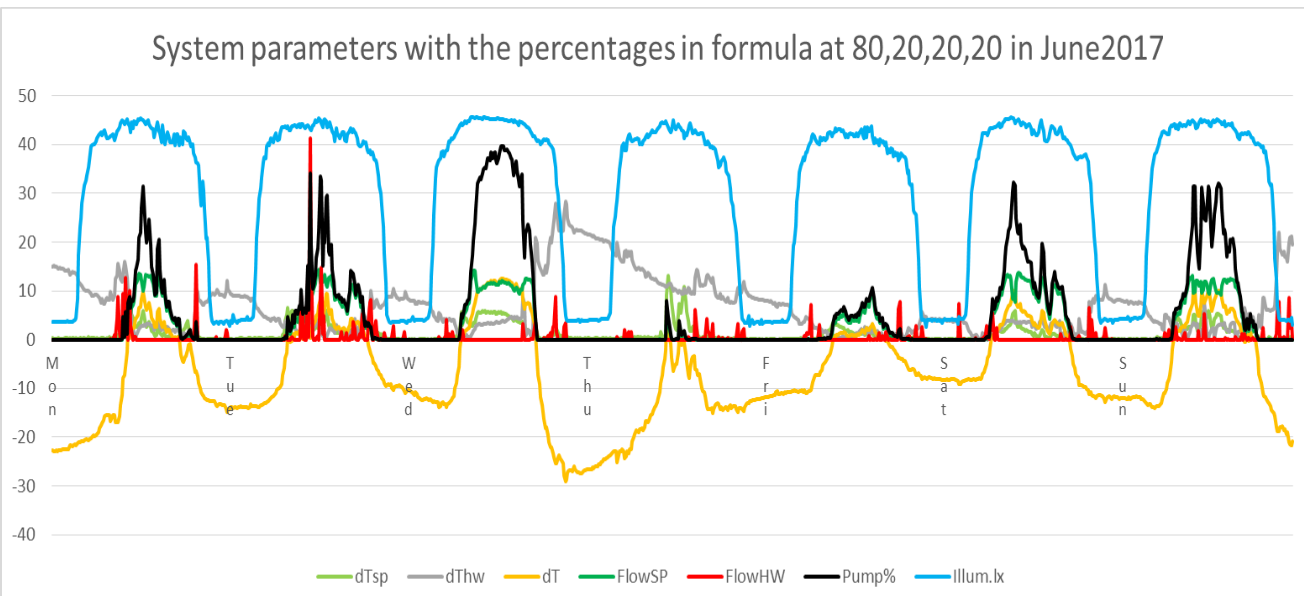

Figure. 9 Data log 24th to 30th of June 2017

Figures 8 and 9 present two weeks data, one in winter, and one in summer with the 'K' coefficients at 80, 20, 20 and 20. From both graphs, one can notice that a good solar input, combined with a high activity on the pump results in the storage tank temperature going up significantly, which then gradually reduces, but also results in there being less need for new input over the next days, independent of demand. Hence, the system not only stores heat automatically, but it also manages to save energy in not pumping the liquids around unnecessarily during this period.

Secondly, one can also notice that any night-time demand is fulfilled by the heat in the storage tank, which, if possible, is then again topped up the next day.

The pump's current consumption is 300mA. Being a 12V pump, the power withdrawn by the pump is 12V x 0.3A = 3.6W. For seven days of continuous usage, the pump would consume: 3.6 x 24 x 7 = 604.8 W. Over the time period specified in Figure 8, the pump was used 2.43% of the total time, meaning a consumption of: 604.8 x 2.43/100 = 14.7 W, while in the time period specified in Figure 9, the pump was used 5.3% of the total time, resulting in a consumption of: 604.8 x 5.3/100 = 32.05W. On top of that, one needs to consider the power consumption of the control circuitry (Arduino, the temperature sensors and the flow meters), which is: 0.28A x 5V = 1.25W.

Based on the larger data set, it was noticed that during the cold periods, the pump works 2 – 3.5% of the total time while during the warm periods, it works 4.5 – 7% of the total time. These reduced power consumptions would obviously be more beneficial if the system is connected to the mains supply. However, the system's electrical demand is currently supplied from a PV solar panel covering the system's needs and charging the backup battery used during night time.

Based on the provided graphs, one can notice that the solar thermal system provides for a certain amount of the thermal demand to this domestic property, but the boiler may still need to top up to supply the full demand.

Within this context, one can determine the quantity of energy delivered by the solar thermal panel to identify the total gas savings. The calculation of the energy delivered by the system is based on the fact that the system should deliver water at 65°C.

The quantity of energy delivered by the solar thermal system is:

$$Q_{SHWSystem} = m_{HW} c_{HW} \Delta T_{HW} \ [KJ] \qquad (6)$$

Within this formula, the hot water mass (m_{HW}) is calculated from the hot water flow rate (FRHW), using:

$$\mathrm{FRHW} = V_{HW}/t = (m_{HW}/\rho_{HW})\ /t\ [m^3/s] \quad (7)$$

Where V_{HW} is the volume of hot water circulating through the circuit, t represents the time and ρ_{HW} is the water density. This water density changes with temperature as shown in Figure 10. Considering the system's working temperature, the density only fluctuates about 1% and can therefore be considered constant, at a value of 996 kg/m^3, for the purpose of our calculations. Resulting in the water mass being: m_{HW} = 996*FRHW*t. Considering the specific heat for water c_{HW} = 4190 [J/Kg], the quantity of thermal energy becomes: $Q_{SHWSystem}$ = 996 *FRHW*t*4190*ΔT_{HW}.

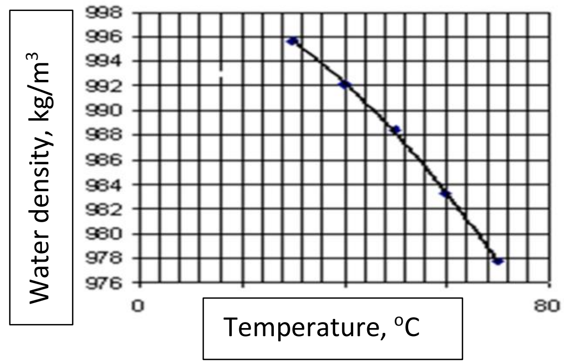

Figure 10: Water density vs temperature [8]

Figures 11 and 12 represent a week's data analysis and show the amount of energy produced by the solar thermal system and the amount of energy produced by the gas boiler in order to meet the thermal demand set at 65°C. From these graphs one can notice that in most cases the demand is supplied by a combination of both sources, but during the sunny periods there is a lower contribution needed from the gas boiler, which indicates that the solar thermal system's pump speed should not only be driven by the demand itself.

In June (Fig.12), the quantity of the energy produced by the solar thermal system covered is a much bigger proportion of the house's energy demand.

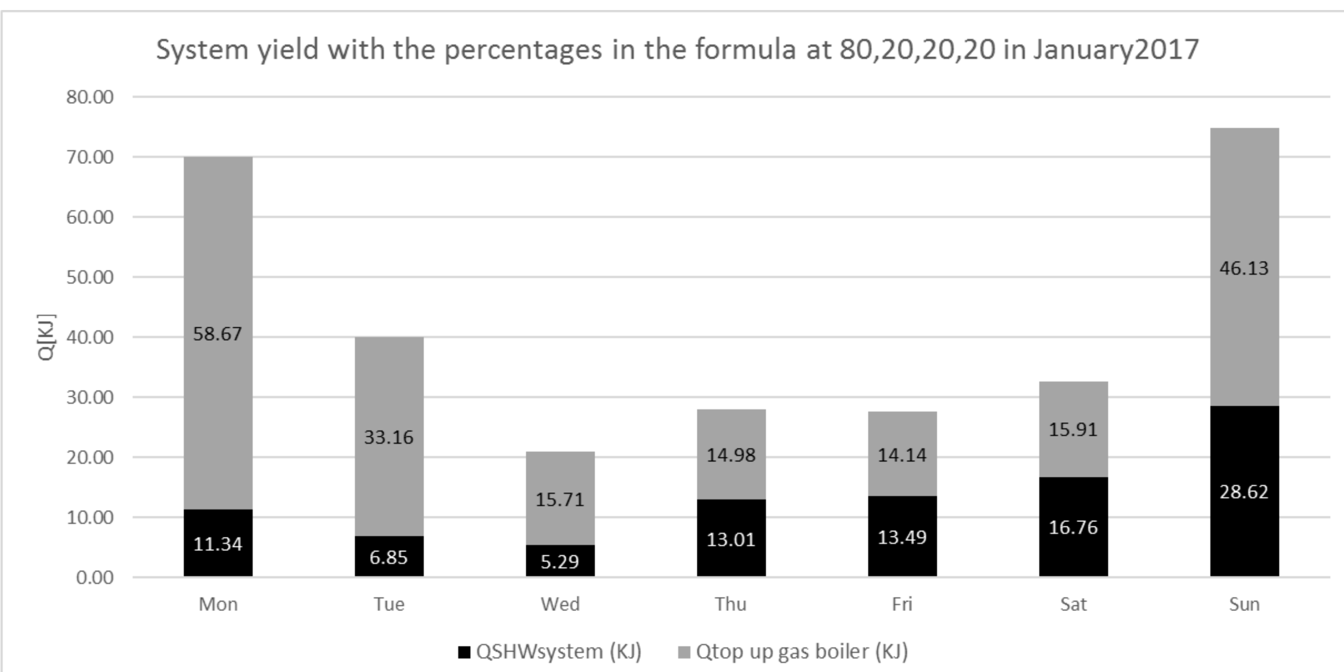

Figure. 11 Data log 9th to 15th of January 2017

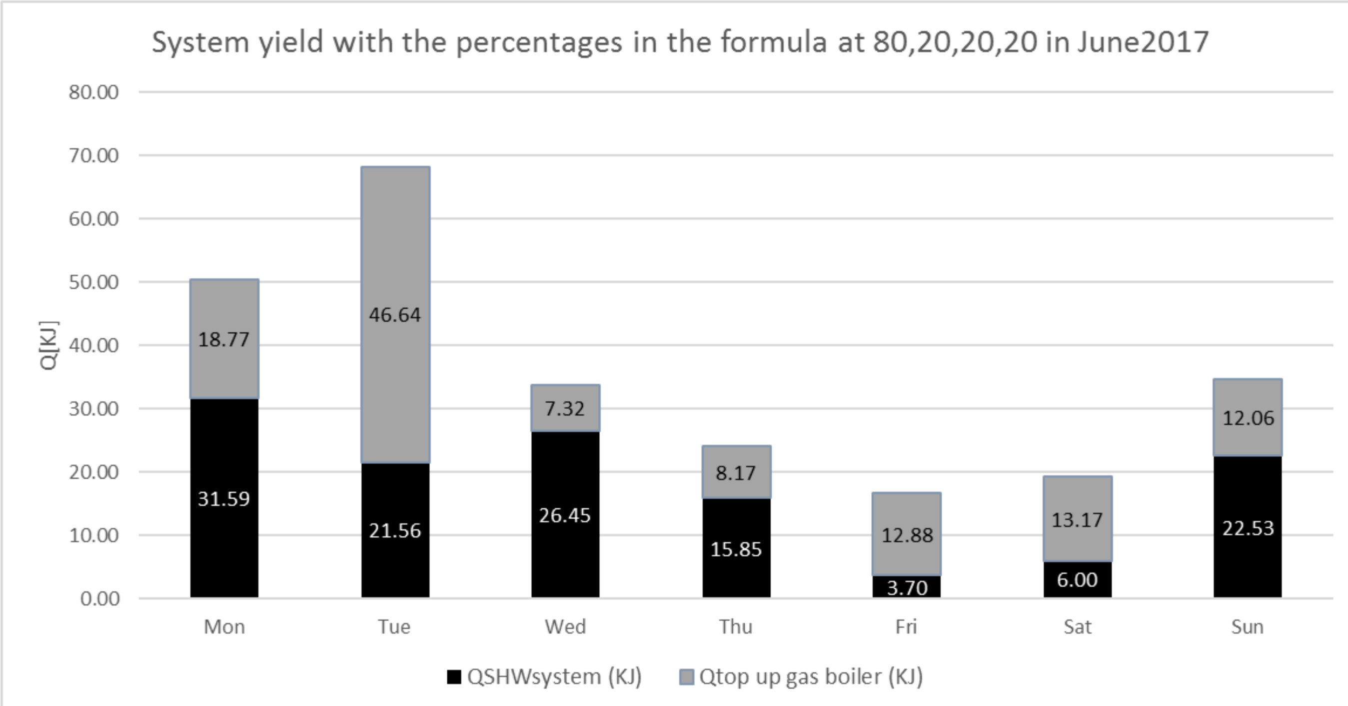

Figure. 12 Data log 24th to 30th of June 2017

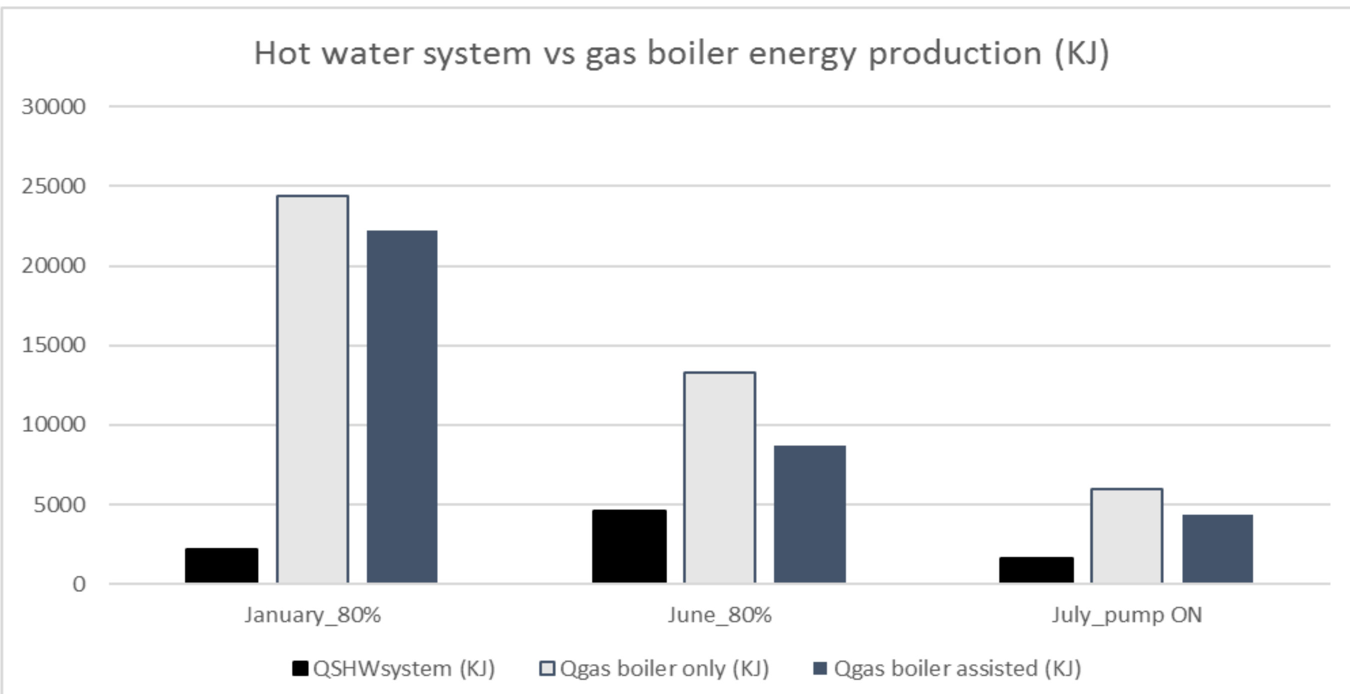

Figure. 13 Comparison of the energy production between hot water system and gas boiler

In summary, the savings achieved due to the introduction of the solar thermal system with the existing gas boiler are summarised in Figure 13 for the various situational setups of the solar thermal panel. The graph shows the data collected for a full month. Within this graph, the energy produced by the gas boiler without the help of the solar thermal system is represented by $Q_{gas\ boiler\ only}$, while the energy produced by the solar thermal system is: $Q_{SHW\ system}$ and the energy produced by the gas boiler working concurrently with the solar hot water system is $Q_{s\_gas\ boiler}$. This graph once more shows the higher heat demand in the winter, while the summer data reinforces the fact that the 80/20 setting is more beneficial with regards to harvesting solar heat. Looking at the graphs representing the energy produced by the solar system in summer, one can see that by using a pump speed controller, the quantity of the energy harvested by the system is more than double compared to an uncontrolled system.

CONCLUSION

This work shows the importance of considering the relationship between solar illumination, harvested heat and the actual water consumption. The system is designed and tested in a domestic property with three-bedrooms and four residents. It is shown that by adjusting the pump speed, the heat exchange can be optimised while the energy consumption is reduced and that while the overhead needed to adjust the pump speed remains minimal. Supplying the full hot water demand with this system is unfortunately not possible, although this is partially climate related and so other environments may obtain larger benefits from such an installation, however it is also clear that adjusting the parameters that determines the pump speed can help to improve the overall efficiency.
Within this context, further work will be performed on optimising these parameters, although it is expected that this may require time due to the environmental (demand and climate) impact on the system as such. A further improvement lies in the introduction of an electrical heating element that is driven by a small windmill and so could aid with heating up the water when solar energy is lower, such as in colder/windier weather, and at night.

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