Department of Mechanical and Aerospace Engineering

Investigation of the possible implementation of weather forecast and demand prediction in a smart control scheme for solar domestic hot water systems

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Signed: SophieVivaudou Date: 6 Septembre 2014

Abstract

Solar Domestic Hot Water (SDHW) systems can offer a great opportunity to meet the hot water demand while using a widely available renewable source. It can be seen that the control of SDHW distribution networks can have an important role to play in the efficiency of such systems. A well installed and controlled solar water system can work efficiently and provide up to 60 % of an annual household hot water demand. However this number can fall as low as 9% if the system is poorly controlled. It is envisaged that the forecast of the suns' energy input, coupled with the predicted hot water demand, could be beneficial for the enhancement of SDHW system controls. The project investigates the possible implementation of these two parameters in a smart control scheme for solar domestic hot water systems.

A prediction and control algorithm was created in Excel, integrating a model of a standard UK SDHW system. This program uses inputs associated with weather forecast, user demand patterns, system heat losses and system solar input to predict the energy state of the system on an hourly basis for the following twenty four hours.

The algorithm was tested for different weather conditions and for diverse periods of the year. And it was found that the solar fraction could be increased by modifying the settings of the back-up system. It was observed that different situations will require different control settings. Therefore, the information regarding weather forecast and demand prediction could be beneficial in order to make a good control decision.

Due to the potential advantages of such improved controls, a last step of the project was undertaken to show the system integration and to propose solutions on how the prediction algorithm created could be implemented into a practical control system.

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1. Introduction

In the UK, Domestic Hot Water (DHW) is typically prepared by means of gas, mainly, but also electricity, oil and coal. These fuels present two main limitations in their usage: they are only available in restricted quantities and they can involve a high source of pollution, having great CO2 emissions (except for electricity, if generated from renewable sources or nuclear). In a context where governments and policy organisations are pushing, not only industries, but also householders, to reduce their emissions and energy consumptions, sustainable solutions for small-scale installations are becoming a leading trend.

As it can be seen in Figure 1, Domestic Hot Water (DHW) account for about 25% of a UK household's energy consumptions, and is the second largest energy consumer after space heating for the residential sector:

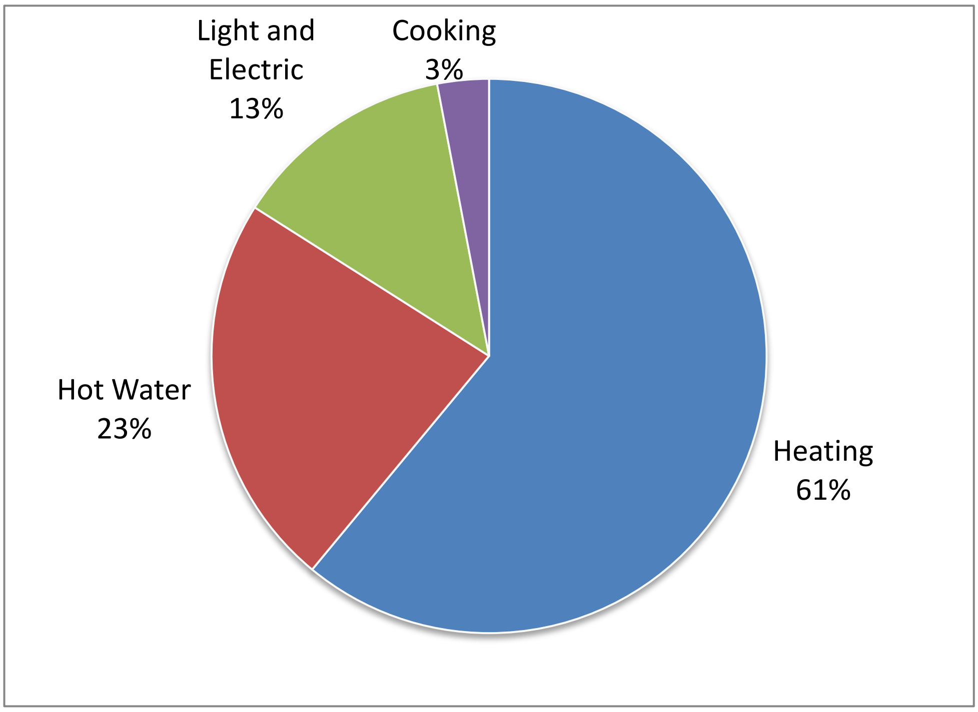


Figure 1- Typical household's energy consumption in the UK

Source: (Act on Energy, 2008)

Solar Domestic Hot Water (SDHW) systems can offer a great opportunity to meet with the hot water demand while using a widely available renewable source, i.e. the sun. In the UK, well installed and controlled solar water system can work efficiently and provide up to 60 %

of an annual household hot water demand. However this number can be drop down to 9% for not properly used or configured systems (Energy Saving Trust, 2011). It can be observed that SDHW systems cannot rely just on the solar energy and need to integrate back-up systems, known as auxiliary heaters, that are usually gas or electricity powered. It was perceived that the control of the solar systems can have a great role to play to maximise the amount of energy provided by the sun and try to minimise the use of the back-up system. This project fixed its interest on the control of these auxiliary systems in order to try to diminish it contribution to water heating, so that the SDHW system consume less non-renewable fuel and reduce both carbon emissions and costs.

1.1. Motive and objectives

As it was observed above, SDHW systems can greatly exploit the solar energy and the portion of hot water supply by the solar system (solar fraction) can be increased if the system is control properly. The peak demand for domestic hot water typically occurs in the morning, when the solar energy is generally not very high, and in an usual control pattern, the water heater systems would use the back-up system to charge the tank in prevision of this high demand. However, sometimes, the solar energy is available in the morning (especially in summer) and it becomes unusable if the back-up system has operated and if the temperatures in the hot water storage tank have reached high values. Actually the solar system can only run if the temperature that it would supply to the storage tank is higher than the temperature at the point it is provided to the tank. It is then a great challenge to succeed supplying satisfactory water temperatures to meet the demand at all times while taking full advantage of available solar energy.

It was thought that the knowledge of the predicted sun radiation and hot water demand could be beneficial in order to enhance the solar fraction. Actually if it is known when the solar energy is available it is possible to try to modify the back-up system settings in such a fashion that the temperatures inside the storage tank would allow for the solar supply to take place. The information about the predicted demand would help with settled the back-up system as it would be possible to see if there would be enough energy in the storage tank to match the demand (back-up set to OFF) or if it would require more (back-up set to ON).

Ways of acquiring good predictions for these two parameters were investigated along with their practical implementation into smart control scheme for solar domestic hot water systems.

The objectives of this project are the followings:

- To investigate solar hot water systems and control options.
- To examine weather data availability for forecasting renewable contribution to solar systems.
- To predict hot water demand, based on user specifications and interface.
- To create a prediction algorithm that forecasts the state of the hot water system for the next 24 hours and can support control decisions.
- To examine a practical implementation with a user interface for the control algorithm proposed.

In order to achieve those objectives, a methodology was undertaken. The next section will discuss how the project was approached and how this thesis will be ordered.

1.2. **Aim, approach and structure of the project**

The overall aim of this project is to investigate the possible implementation of weather forecast and demand prediction in a smart control scheme for solar domestic hot water systems.

In order to complete this target, distinct steps were undertaken. This section will underline them so that the project lines are clear and well understood.

A first step that implicated scoping, investigation and knowledge gathering was followed by further analyses involving the proposal and testing of a potential solution. Finally discussion were hold regarding the outcomes, potential future work and conclusions of the project.

The scoping steps, presented in the literature review, were:

- Solar systems: The first scoping step consisted on an examination of the solar hot water systems with the purpose of having a good knowledge of the technology. This work also helped with the selection of the system(s) to consider during this project.

- Control: With this later part well defined, the control of such equipment was analysed. The existing control algorithms and their eventual short-coming needed to be comprehended to allow a smart(er) control scheme to be proposed.
- Weather and demand forecast: The availability of weather data for smart control and how this could be accessed was explored with a view to critical solar and temperature parameters.
- Case study: Smart control proposals from literature, including the EU ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) project, and the Dunoon Passive House project(s), were reviewed to see what potential smart controls had been proposed elsewhere.

Following these scoping works, a technical approach was set in order to attain the aim of the project. The underpinning prediction and control algorithm and modelling approach was adapted from the proposed community scale ORIGIN approach and from what was used in some Dunoon previous work. It was decided to develop and demonstrate the control algorithm in Excel, using the basic functionalities of this program and also Visual Basic for Applications (VBA). The algorithm approach, logic and how it is implemented in Excel is explained.

The algorithm has a model of the system and needs inputs from weather, user demand pattern, user default control settings, system heat losses and system solar input. The ORIGIN cloud based, community level project is developing solutions for learning the system heat loss and solar input characteristics based on weather conditions and these will be used in this case also. Key challenges are then to develop a system level solution which can access and use weather data to support smart control algorithms which will adapt to different user patterns and can be implemented on a practical platform. To address this, four different profiles were created in Excel:

- A profile showing storage losses in the tank, based on an Audit.
- A demand profile for a typical week based on an Audit and user specifications.
- A sun forecast profile with is based on a methodology that was developed for importing and processing the required weather parameters for use in the Excel algorithms.

- A hot water production profile, based on the sun forecast profile and on an Audit. This will allow for the translation of weather data into solar input data (using an adaption of the UK Standard Assessment Procedure (SAP) method).

The creation of the algorithm profiles and the final outputs from it are presented in chapter 3.

In a next section, the operation of the algorithm is demonstrated using the Excel model for different weather conditions and different period of the year. Results are then analysed and ways to obtain optimal timing for the back-up system are proposed.

The last step of the project shows the system integration and proposes solutions on how this system could be translated into a product. Discussions about the profile modifications thanks to potential monitoring work inputs will be held. In a real-life project, monitored data could be used in order to generate more accurate profiles, based on real system performance data, for each of the area stated above. These more precise models will be developed using multiple regression analysis. It will be shown how this monitoring work could be accomplished and example of regression analysis completed within the ORIGN project will be exposed. Then, it was though that if smart algorithms incorporating weather data are to be useful, they need to be implemented on a practical way with a controller that can run it and deliver its outputs to the system. The current solutions were evaluated and discussed to comprehend what would be best suited for the proposed smart control functions. Then, some consideration was given of user interfaces.

Finally, discussion, future work and conclusions are summarizing the overall study and bringing to a close this thesis.

2. Literature review

2.1. Configuration of Solar Hot Water Systems

The energy from the sun is and has been widely used to heat water. The technology is not new and is well understood. This first section will give a basic understanding of the solar water heating system.

Solar hot water systems have to accomplish the following basics function:

- Collection of the sun thermal energy: solar collectors are used to convert the incident solar radiation into usable thermal energy.
- Transfer and storage of the thermal energy: The thermal energy from the collector is needed to be moved from the point of production to the point of use. This thermal energy is then stored, as the energy from the sun is not necessarily available when there is a demand.
- Distribution and demand match: The thermal energy has to be circulated along the diverse loads and the demand needs to be satisfied at any moment of occurrence.

A detailed explanation of the above functions of solar water heating systems and the description of the different components used to provide those services are developed below.

Collection of the solar radiation

In applications such as solar water heating, the radiation from the Sun is capted and transformed into heat by solar collectors, which can be seen as a special type of heat exchanger.

There are 3 main types of collector:

- Unglazed, which performances are limited by the high amount of thermal losses that this configuration presents.
- Evacuated tube, which is a more recent technology that can provide high heat retention.
- Glazed flat plate that is the most comon design and which will be the one considered in this project.

(BRE, 2011)

For this project it was decided to concentrate on flat plate collectors are they are the most used. Moreover a field trial realised by the Energy Saving Trust states that “there was little difference between the total solar energy yield of [those] installations that used flat-plate solar collectors and those that used evacuated-tube solar collectors.” (Energy Saving Trust, 2011).

Glazed flat plate collectors have a simple design, which can be seen in Figure 2, are relatively cheap and easy to manufacture, and require little maintenance (Duffie & Beckman, 2013).

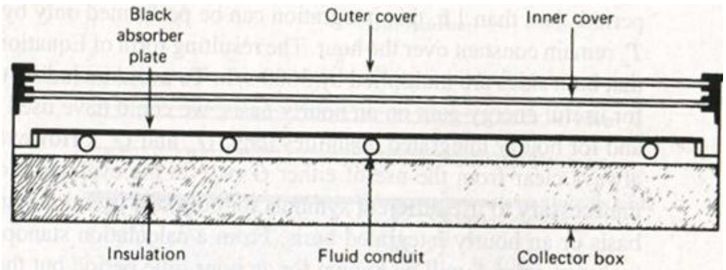


Figure 2 – Cross section of a basic flat-plate solar collector

Source: (Duffie & Beckman, 2013)

In solar water heating applications, flat plate collectors are elaborated to deliver moderate temperatures, up to a maximum of 100°C above the ambient temperature. They use a working fluid to collect the energy and transfer it to the rest of the SDHW system: it can be water, antifreeze (usually non-toxic propylene glycol), or other type of liquid that are able to absorb the solar heat. In climates such as in UK, where freezing temperatures can take place, the flat plate collector will most likely use antifreeze fluids.

The performance of solar collectors are affected by two main factors: the absorption efficiency, also known as zero-loss coefficient η_o, and the heat loss coefficient a_1. The first coefficient, express in percent, indicates the percentage of energy that can be absorbed into the system when the solar fluid temperature is the same as the outside temperature. Higher value for η_o will lead to better performances. In the contrary, $a_{1,}$ expressed in W/m^2K, which represent the energy lost by the pannel and is related to the insulation properties of the collectoer, should be minimised (Worcester Bosh Group, 2014). The relationship between these two values is used by SAP and will be used in this project to find the solar input to the water heating system.

When designing a SDHW system, the tilt and orientation of the collector must be analysed so that the energy capted is maximise with regards to the available solar energy available. Collectors are usually mounted at a fixed tilt angle that is chosen to take advantages of the most useful altitude angles of the sun in order to maximise the solar heat available to heating load throughout the year. In addition, the orientation of the collector must ensure a good exposure to the solar azimuth angles (Stickney, 2010). For the UK, it was found that the ideal tilt will have a 30° inclination and the ideal roof will have an orientation of 90° South but it should be outlined that the inclination of the roof does not play such a decisive role as orientation (Solar Trade Association, 2014).

Transfer and Storage

As solar energy is an intermittent resource, its availability does not necessarly coincide with the time at which the demand occurs. Therefore, the thermal energy collected by the collector need to be transfer and stored until it can be used to meet a specific load.

Regarding the transfer of the thermal energy, solar water heating systems can present two main design:

- The passive systems, is based on natural circulation of the water by convection, from the collector to a tank situated above it. They do not need any extra source of energy to heat the water (no pumps, no controller). Those systems are mainly used in climates where freezing temperatures are not reached (Duffie & Beckman, 2013). Therefore in the circumstances of this project, they will not be further investigated.
- The active systems use a pump to bring the fluid from the collector to the tank. The pump is controlled to be turned on when the heating gain from the solar collector will be beneficial to the tank. Active systems can be design regarding different configurations, with one or two storage tanks, having different arrangement of the auxiliary heater within the tank. However the most common situation in the UK is a combined-storage system that is presented in Figure 3 and that will be the one this project will focus on.

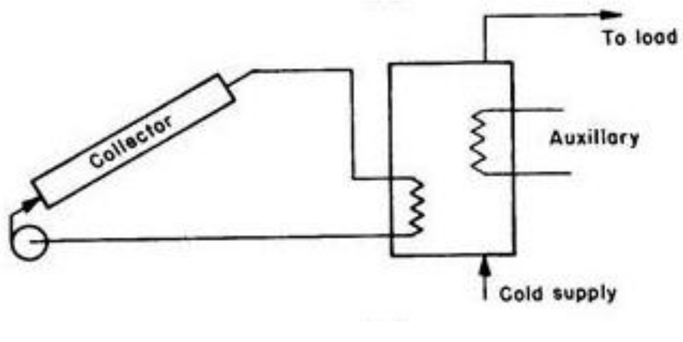


Figure 3- Selected solar system configuration

Source: (Duffie & Beckman, 2013)

In the above system, the working fluid from the collector exchanges its energy with the water present in the storage tank. The pump is controlled to circulate the fluid through the system if its temperature is high enough to supply thermal energy to the storage tank. The pump controls will however not be further discussed as it is not a main motivation of this project.

The storage of the hot water has one main problem to focus on: the legionella bacteria. This bacteria lead to a potentially fatal disease, the Legionnaires' disease, that anyone is susceptible to contract (Health and Safety Executive, 2014). The human infection by this organism is often associated with artificial water system and there is a need to inhibit and limit the growth of these bacteria in such system (BSI British Standards, 2008). The risk of legionella is increased if the water temperature in all or some part of the system is between 20-40 °C, which is a temperature range suitable for growth (Health and Safety Executive, 2014). In a publication from the Scottish government in march2010, it is recommended that:

> "To control the risk of Legionella and similar pathogens, a secondary heat source, typically an immersion heater coil is needed to raise the temperature of the stored water, once a week for a short time, to at least 60°C, in accordance with guidance to the Water Byelaws."
>
> (The Scottish Government, 2010)

For this project, this should be taken into consideration and the temperature of the storage should be controlled as stated above. The need of an auxiliary heater to complete this task will be further discussed in the section "Distribution and demand match" below.

In order to take the most of the solar energy brought in the tank, it is interesting to look at the level of thermal stratification in the storage tank. Hollands and Lightstone (1989) demonstrated that solar hot water systems operating with a thermally stratified storage tank have substantially improved performance, particularly at low flow rates. Stratification is due to the existence of a temperature gradient in the storage that allows the separation of fluid at different temperatures level, the top being hotter than the bottom (Cruickshank, 2009). The degree of stratification in a given tank depends on its own design, on the design of its outlet and inlets and on the flows rates of the entering and leaving water (Duffie & Beckman, 2013).

Distribution and demand match

Because the hot water is not produced at the point of use, when there is a demand, the thermal energy stored has to be distributed through the loads. Depending on the level of insulation of the pipes distributing the hot water, more or less distribution losses will occurs. In this project the algorithm created first relies on profiles that does not account for distribution losses, however it should be upgrade using monitored data that will integrate those losses.

The hot water is leaving the storage tank at the temperature of the top of the tank. It is then mixed with cold water to reach the required temperature. Hot water systems need to be reliable and have to be able to meet the demand at any point. The hot water demand varies with the time of the days, the day of the week, and the month of the year (Vine, et al., 1986). However redundancies in the demand profiles can be found: a typical daily profile shows peaks in the morning and night, generally due to showers and/or baths practises, and smaller peaks around meal times for cooking activities (Vine, et al., 1986). A report from the Energy Saving Trust describes the analysis of data on hot water consumption collected in approximately 120 houses. The Figure4 below shows a typical profile for a representative dwelling from this study:

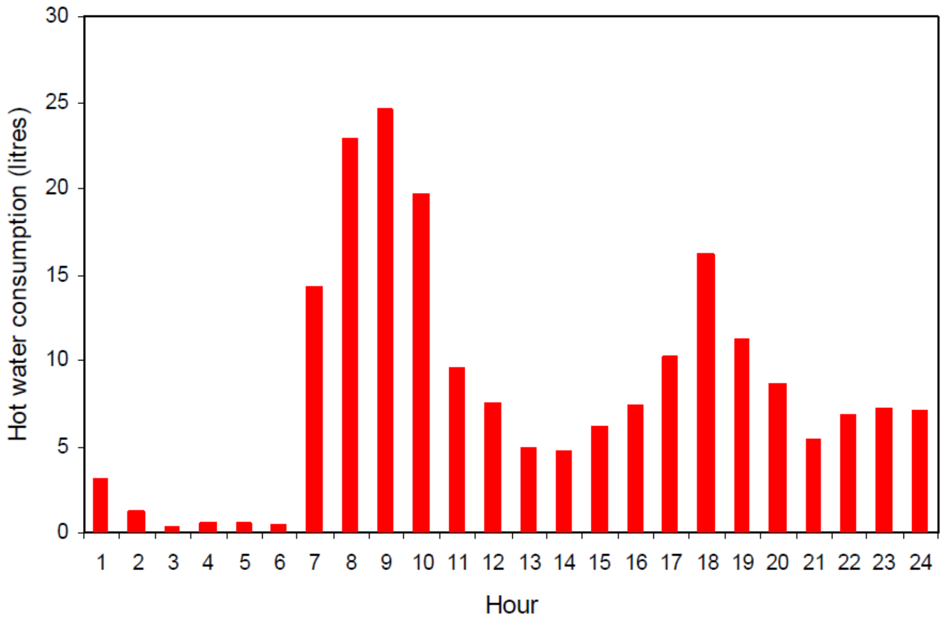


Figure 4- Daily profile of one dwelling

Source: (Energy Saving Trust, 2008)

In order to have a precise demand profile, the algorithm produced during this project will integrate a user specification section where the user can complete his hot water consumptions habits. These consumptions will be calculated assuming certain flow rates for the usually used devices (shower, tap). The systems should also be monitored to base the profile on real data and be able to be as near to the realty as possible.

Another important point to understand here is the need for an auxiliary heater. Actually, in order to prevent legionella and to be able to match the demand at any time, in climate such as the one in the UK, there is a need for an auxiliary system that operates as a back-up and ensures reliability for the DHW system. Thermal energy from the auxiliary heater can be added to the water in three different locations: when the water leaves the tank, before it enters the tank or inside the tank. The latter situation will be the one studied through this project because it is the most common one in the UK. This method is the simplest and has cost advantages, however the main drawback is that the auxiliary heater can sometimes supply too much energy and the increment of temperature in the storage tank can be such that any gains from the solar collector are unusable. Auxiliary heaters can also use different fuel sources, commonly gas (boilers) and electricity (immersion heater or heat pumps). It was seen that a standard solar system would use electric immersion heater and that will be the back-up chosen for this project.

The different configurations of SDHW system have been explained and the options selected for this specific project have been outlined. The next section will described how such systems could be control.

2.2. Control of Solar Hot Water systems and shortcomings

In SDHW systems, there are two devices to control: the solar pump and the auxiliary heater. As it was seen in the above section, the control of the solar pump will not be looked at in this project and it will be assumed that they are set. Further information about their assumed setting will be explained in section 3.4.

The project fixed it interest on the control of the immersion heater in order to consume less electricity from the grid and have lower cost. In an ordinary fashion, a cylinder thermostat is used to sense the temperature of the water inside the hot water storage tank. It will turn the water heating on if the temperature sensed falls below the thermostat setting and turn it back off when the desired temperature is reached. The cylinder thermostat should usually be set for a desired temperature between 60°C and 65°C (Invensys, 2014).

However, for solar water system, this kind of control lead to a conflict if the tank temperature falls below the set temperature just before a solar radiation occurs. Actually, in this case, the back-up system will turn on and heat the stored water so that the previously available solar energy could not be harvested. The Figure 5 below shows how a bad control of the back-up system can lead to the loss of the supply from the solar energy:

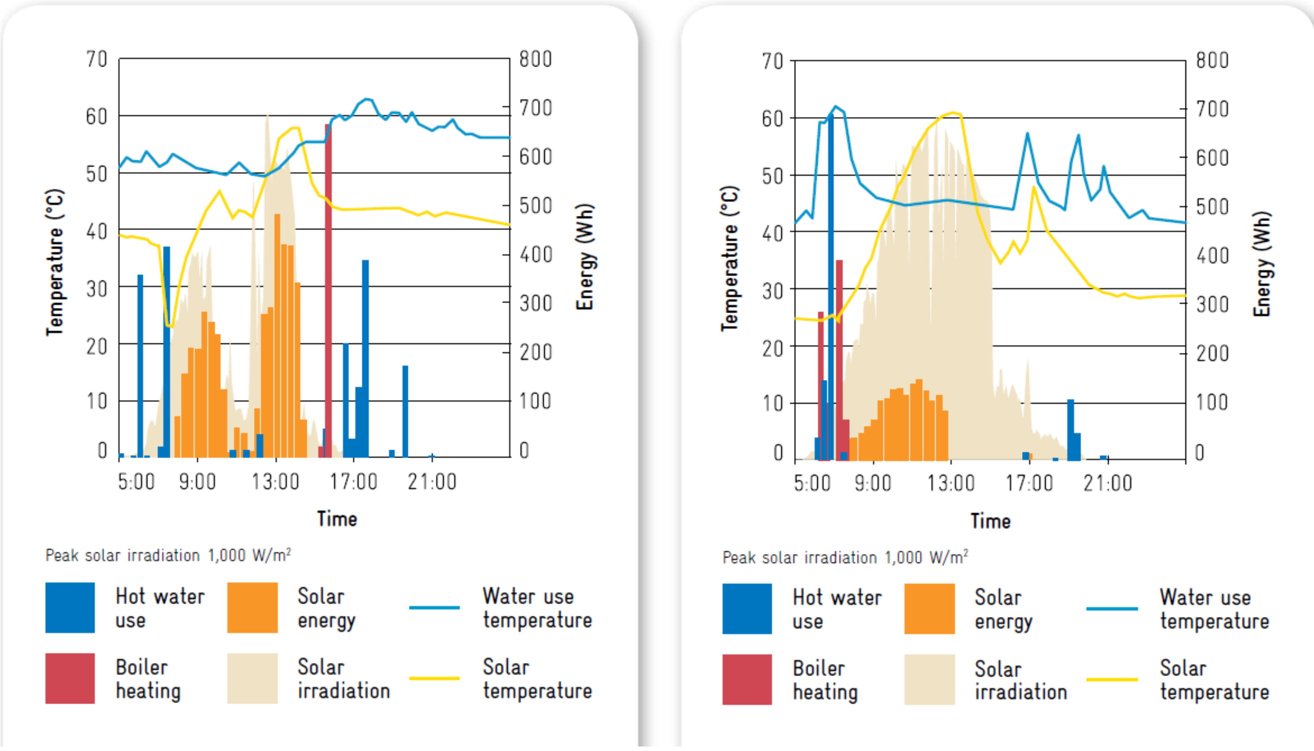


Figure 5- Example of well-timed (left) and poorly timed (right) back-up heating use

Source: (Energy Saving Trust, 2011)

On the left end side, it is seen that the back-up system (a boiler in this example) turn on just after the solar supply occur and just before the hot water use. The solar radiation is well harvested as it can be seen that it provided a reasonable amount of solar energy (in orange in the figure) to the system. In the right end side however, the boiler fires in the morning, even though it is a sunny day, with high quantity of solar radiation available. The result is that only a minor portion of the available radiation is actually provided to the system.

In this project, as the storage tank offer a large storage capacity, it was thought that it would be economically beneficial to charge the tank during the off peak period, e.g. between 12-midnight and 7am, as it offer advantageous tariffs. These settings were put as default but they should be updated if the prediction algorithm developed during this project finds other appropriate time that would maximise the solar energy provided to the system.

2.3. **Case study: Findhorn Community**

For this project, a case study was taken in order to be able to demonstrate the algorithm with some real data. The Findhorn Eco-community presented a suiTable opportunity as it is part of the European Union ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) project.

The ORIGIN project is an EU founded project that aim to develop an intelligent system for the management of energy in community, focussed on the concepts of aligning energy demand with the availability of renewables-based supply (ORIGIN, 2012).

The system to be created will comprise algorithms for prediction of demand and supply, optimization of energy management actions, and continual control of all software and hardware elements across the energy network. The hardware basis includes smart meters in buildings, actuators for selected devices, one or more central servers, and an associated communications infrastructure (ORIGIN, 2012). In this thesis some methods used are based on what the ORIGIN project are carrying out, as it has a similar approach, with the exception that this thesis is focussing on individual buildings, and not communities, and that it just looks at domestic hot water and no other energy demand. Data from the monitoring work realised within Findhorn Community by ORIGIN will be used to demonstrate the algorithm for a real-life case.

The Findhorn Community counts approximately 450 residents with approximately 120 residential and 30 commercial buildings. The community integrates 90 ecological buildings and a 750kW wind farm comprising 3 off Vestas V29 225kW turbines and 1 off Vestas V17 75kW. In addition, 25kW of solar-PV is installed and 15 solar water installations are connected directly to dwellings (Girona, et al., 2014) (The Findhorn Foundation, 2014).

The project mostly concentrates on system similar to the Centini houses because they integrate a 500 litres storage tank. This provides a great opportunity for load shifting and storage. The storage tank used by those houses is a ROTEX Sanicude Solaris (see Appendix 1 for full specifications). In this storage tank, the water delivered to the users is not really stored in the tank but is taking the energy from the tank through a heat exchanger. For this project the specifications regarding the storage losses and the dimension of the tank were used but the DHW were supposed to be actually store in the tank as this represent a more standard system that can be found in the UK. Moreover stratification was assumed in the store. The following specifications were used for the project:

- The tank has a capacity of 500 litres with a height of 1.59m.
- The heat loss given by the technical data was used to calculate the storage losses in section 3.1. of this thesis.

The specifications from the solar collector were as well used. It was known that the Centini house used a collector from AES solar system which specifications can be seen in Appendix 2. This data were used to calculate the hot water production as it can be seen in the section 3.4. of this thesis.

Finally, it was seen that the Centini houses use an electric immersion heater as a back-up to the solar system with is a common configuration for SDHW system in the UK and the one chosen for this project. As no specific values were found for the power of immersion heater used in the Centini houses, it was assumed from the tank specification, which stated that this kind of store come with an electrical back-up of 2.4kW.

2.4. **Conclusions**

The configuration of the solar systems was understood and the importance of the control in those structures was outlined. The case study used in this project was described and the modifications made to the system found in the Findhorn community were defined. It was decided to focus on one precise arrangement presented in Figure 6 below, which was seen as being a common UK system.

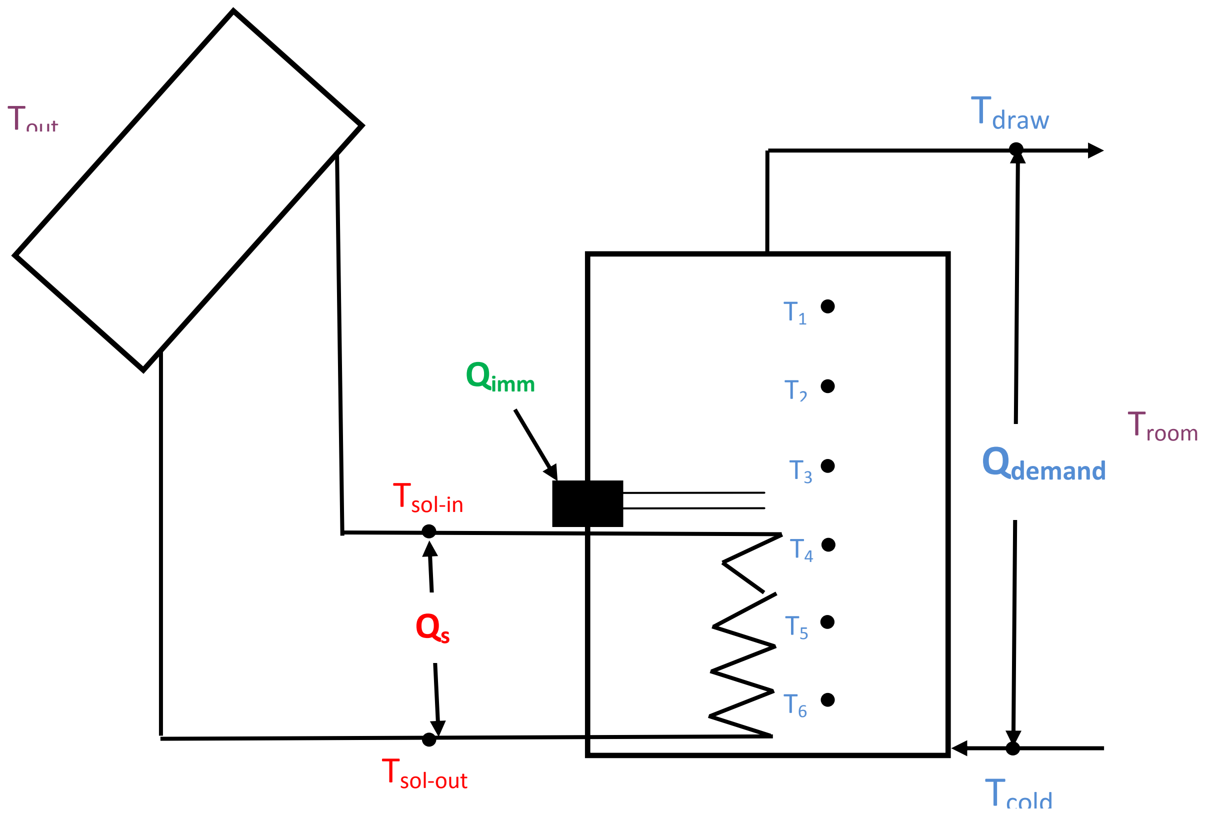


Figure 6- SDHW System studied

In the above Figure, it can be seen that the solar energy input Q_s transported by a working fluid is delivered to the hot water storage tank through a heat exchanger, at a temperature T_{sol-in}. The working fluid then returns to the collector at a temperature $T_{sol-out}$. In the storage tank, diverse nodes can be identified, each of them having different temperatures: T_1, T_2, T_3, T_4, T_5 and T_6. When a demand occurs, there is a draw from the storage tank at a temperature T_{draw}, and at the same time water is refilling the tank at the bottom, at a temperature T_{cold}. The necessary energy for the demand is Q_{demand}. The temperature of the draw is actually equal to T_1, the top temperature of the tank, and will be adjusted to the adequate temperature of use later in the distribution system, by the means of a mixing valve. In case of low input from the sun, additional energy Q_{imm} is provided by the electric immersion heater, having a 2.4 kW power rating.

With the system seen in Figure 6, an investigation regarding ways of providing improved controls will now be undertake. The next part of this thesis will present the prediction algorithm that was developed in Excel in order to support control decision.

3. Prediction and Control Algorithm

The algorithm aims to predict the state of the solar hot water system for the next 24 hours based on weather forecast and demand forecast and an underpinning model of the system, including storage losses with a one hour time step. These predictions will then be used to make control decisions that will optimise the performance of the solar system and its back up heater use.

In order to complete this task, it needs to know what will be:

- The storage losses
- The user demand profile
- The weather forecast, here focused on sun radiation forecast
- The solar hot water production
- The backup heater settings
- The underlying system performance model and state of the system

The algorithm relies on profiles, based on an Audit, on user specifications and/or on weather forecast from the Internet.

The profiles presented in this section were produced to be able to run the control system during the 5 week monitoring work and/or in case this work could not be realised. A real data based equation model using multiple regression analyses, supported by this monitoring work, should then provide more accurate profiles regarding the characteristics of the solar system. This point will be discussed in the practical implementation in section 5.

In this part of the thesis, the four models created will be present, outputs from the algorithm will be exposed and conclusions will be drawn. To have a good appreciation of how this can all work together, the system presented in the conclusions of the literature review will be used to demonstrate the profiles.

3.1. Storage losses profiles

When hot water is stored for a certain amount of time, modification in its temperature occurs, even if there are no water draws or heat inputs from the water heater system. The profile produced is based on previous work from former student, Lewis Bowick, and was also utilised in the first steps of the ORIGIN project. In the case of a stratified tank with six different nodes, as the one chosen for this project, each node temperature will experience natural losses due to its interaction with the environment and with the other node. In the profile created, only the interface with the environment was considered, as it was seen in the previous work that it gives good approximations of the state of the system. Moreover, the relations between nodes imply challenging fluid dynamics that would significantly have complicated the project.

The following Figure illustrates how the temperature of the water in the storage tank can evolve from one state to another. This is a fictional example, as details of the temperature evolution will be discussed just below.

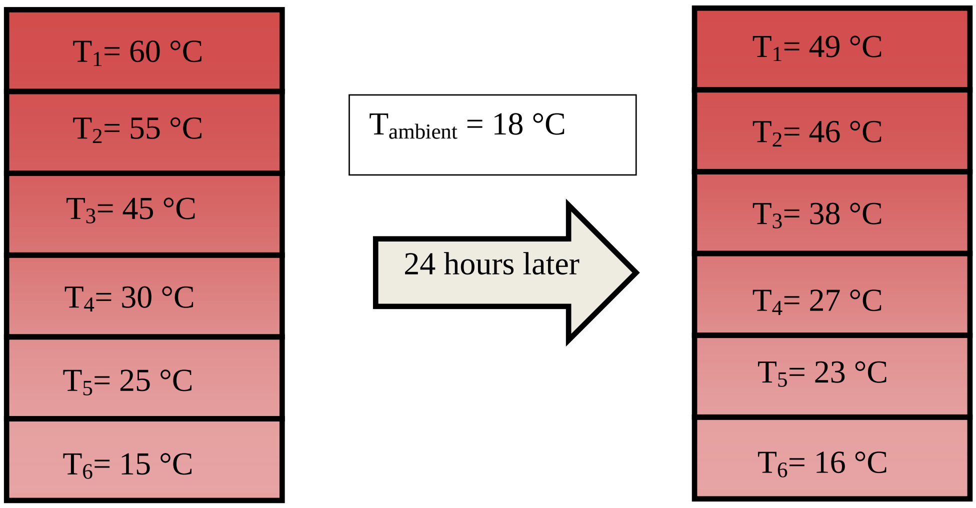


Figure 7 (a) - Initial state

Figure 7 (b)- Future state

Figure 7- Fictional temperature evolution of the hot water in the storage tank

For the construction of the storage losses profile, the initial state of the tank was taken as the one shown in the left in Figure6: T_1=60°C, T_2=55°C, T_3=45°C, T_4=30°C, T_5=25°C, T_6=15°C and a surroundings temperature of 18°C. These temperatures were chosen to have something to start with but they should be actualised with the value received from sensors temperatures each time that the algorithm is run.

The storage losses are calculated using two common equations employed in energy calculations: $Q = U \times A \times \Delta T \times t$ (1) and $Q = \frac{m \times cp \times \Delta T}{3600}$ (2).

Those two equalities need to be solved for each node, using data of the case considered, e.g. Findhorn Community.

- <u>Resolution of equation (1):</u>

$Q_{(1)} = U \times A \times \Delta T \times t$, where $Q_{(1)}$ is the energy loss in Wh

U is the heat loss in W/m^2K

A is the area in m^2

ΔT is the temperature gradient in K

t is the time in second

This first equation was used to calculate the energy loss for each of the 6 nodes of the storage tank, during the next 24 hours, with a one hour time step. Therefore t= 1h=3600s.

The temperature gradient used is initially based on the initial conditions of the storage tank and the surroundings as seen in Figure2a above. For example, if the node 1 is considered, it temperature T_1 is 60°C and the ambient temperature $T_{ambient}$ is 18°C, hence the $\Delta T_{(node\ 1)}$ is 42K.

The area, in this case, is considered to be the side area of the node considered. For a cylinder, the side area is calculated using the formula $2 \times \pi \times r \times h$, where r is the radius and h the height of the cylinder. As all the nodes are assumed to have the same dimensions, the result from this equation is then divided by 6, to have the area of the node studied. In the case study analysed, the cylinder has a radius of 0.32m and a height of 1.59m (see Tank specification in Appendix 1) so the area of the side of this tank is $3.16m^2$ and therefore the area to take into account in equation (1) is $0.53m^2$.

The U-value calculation is slightly more complex as this rate is not clearly stated in the technical data available for the storage tank considered. The tank technical specifications however stipulate that the 500 litres ROTEX Sanicube has the following characteristic regarding the heat loss:

"With a middle storage tank temperature of 58 °C and an ambient air temperature of 20 °C, the heat loss is only of 82 W ...etc."

(Rotex, 2006)

Moreover, the tank is 1.59m high and 0.79m wide (see Appendix 1), which give an area of $1.26m^2$.

If the following equation is used:

$Q = U \times A \times \Delta T$, with Q is the heat loss, here Q= 82W

A= is the total area of the cylindrical storage tank, that has a radius of 0.32m and a high of 1.59m, so

$A = 2 \times \pi \times r \times h + 2 \times \pi \times r^2 = 3.79m^2$

ΔT is the temperature difference, $\Delta T = T_{tank} - T_{ambient}$ =58-20=28°C.

It is found that the U-Value for this storage tank is 0.78 W/m^2K.

The values required to solve the equation (1) are now available and the energy loss can be calculated for each node, for the next 24 hours.

- <u>Resolution of equation (2):</u>

$Q_{(2)} = \frac{m \times Cp \times \Delta T}{3600}$, where $Q_{(2)}$ is the energy loss in Wh which is equal to $Q_{(1)}$

m is the mass of water present in one node considered, here, for a 500 litres tank, if the density of the water is assumed to be equal to 1000 kg/m^3,the mass in one node is 500/6=83.3 kg.

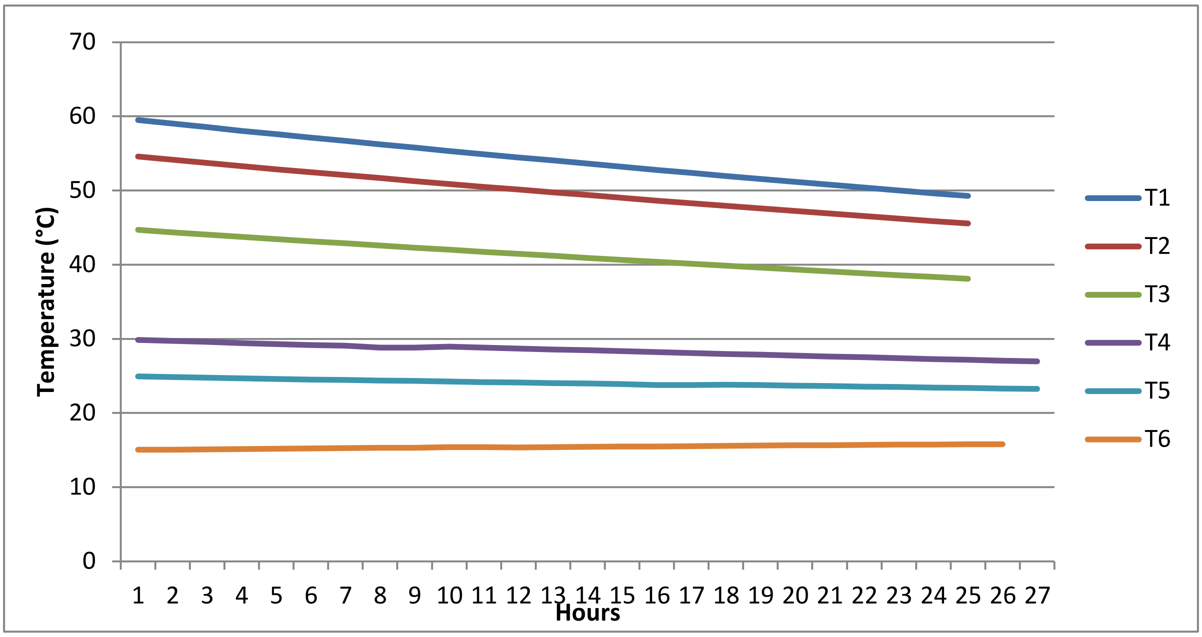
c_p is the heat capacity of the water, here assumed constant, with a value of 4180 J/kgK.

ΔT is the temperature gradient in K

This equation was used to calculate the temperature of the node at the end of the one hour step, $T_{(node+1)}$. The temperature gradient is therefore the difference between the node temperature at the end and the one at the beginning of the hour. For example, if node 1 is considered, ΔT will be equal to $T_1 - T_{(node1+1)} = 60 - T_{(node1+1)}$

As $Q_{(1)} = Q_{(2)}$, and $Q_{(1)}$ was solved previously, it is possible to extract the temperature of the node, after the energy loss occurs, e.g. after the hot water was stored for one hour.

With these two equations, it was possible to model the temperature modification in the storage tank by loss to the environment and the results are shown in the Graph 1 below.



Graph 1- Temperature drop due to losses to the ambient

From the above Graph, it can be seen that the three top tank temperatures experience a high lost as there are much warmer than the ambient temperature. The three bottom curves however have a small slope and are not facing high losses, the temperature in node 6 having even some gains from the environment. The storage losses have been defined and compute in Excel, the construction of the demand profile will now be explained.

3.2. Demand profile

The demand profile was created based on user specifications and on auditing measurement. The audit will give information about flow rates for the shower head and for the kitchen tap. For this model it was assumed that those 2 devices were the main source of hot water demand and therefore they were the only two considered. In the model, as no specification were found for the specific case of the Findhorn community, the flow rates were calculated with regards to the Plumbing Engineering Services Guide. This later state that typical tap and showers would have a 0.2l/sec and 0.08l/sec flow rates, respectively (The Instute of Plumbing, 2002). The later values were used in l/min for this project, so the followings were utilised:

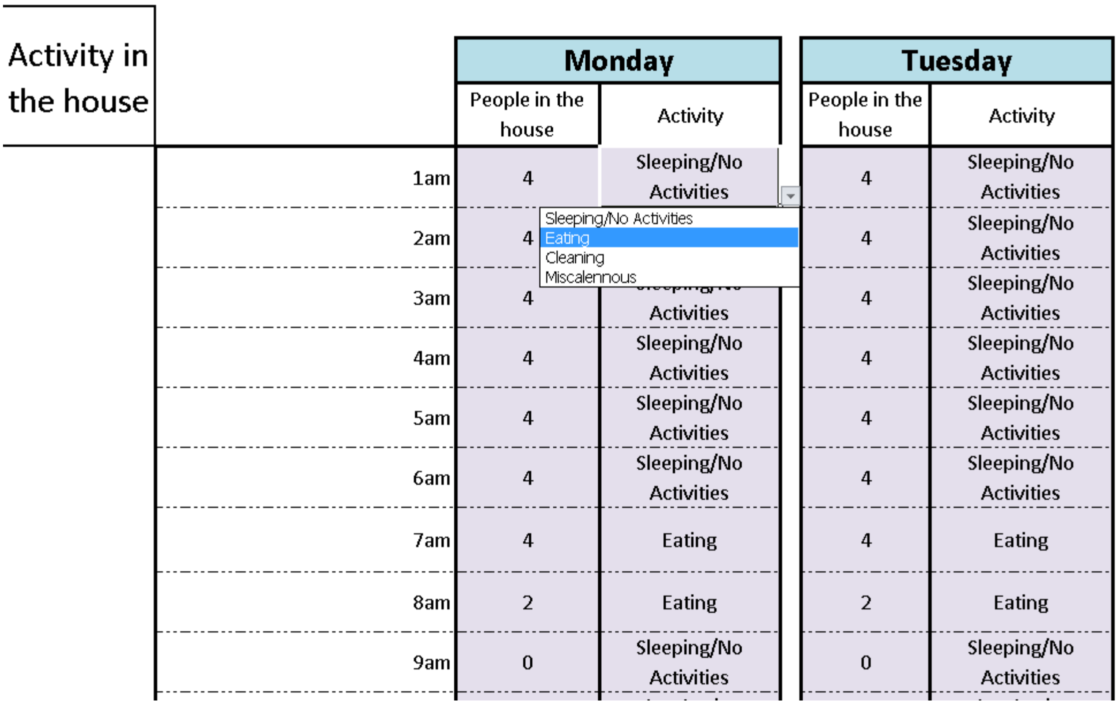
- Shower Head Flow Rate = $\dot{m}_{shower}$= 4.8 l/min.
- Tap Head Flow Rate = $\dot{m}_{sink}$= 12 l/min.

To enable a better understanding, a first fictional example of two adults with two children living in the house, working/studying weekdays, was taken.

The user has to complete two different kinds of timetable:

- The activity timetable: it provides hourly descriptions of how many people are present in the house and what are their activities.
- The shower and bath timetable: it has to be complete individually, for each occupant of the house, and state the times at which the showers and/or baths are taken.

An example of the activity timetable is shown in Figure 8 below:



Activity in the house	Monday: People in the house	Monday: Activity	Tuesday: People in the house	Tuesday: Activity
1am	4	Sleeping/No Activities	4	Sleeping/No Activities
2am	4	[illegible]	4	Sleeping/No Activities
3am	4	Activities	4	Sleeping/No Activities
4am	4	Sleeping/No Activities	4	Sleeping/No Activities
5am	4	Sleeping/No Activities	4	Sleeping/No Activities
6am	4	Sleeping/No Activities	4	Sleeping/No Activities
7am	4	Eating	4	Eating
8am	2	Eating	2	Eating
9am	0	Sleeping/No Activities	0	Sleeping/No Activities

Figure 8-Activity timetable

In this model, the user can choose between basics activities that could potentially consume hot water. For each, a time of two minutes during which the water will be running was assumed. This time can easily be changed. Then, this given time was multiply by the flow rate of the tap to give the litres consumed for specified activity. From a study realised by the Energy Saving Trust, it was found that the cold inlet water temperature has a mean value of 15°C and that the tap delivered a mean temperature of 38°C (Energy Saving Trust, 2008). By using the same equation that the one used for calculating the storage losses, $Q = \frac{m \times Cp \times \Delta T}{3600}$, and assuming that the density of the water is 1000 kg/m^3 (1litre of water is equal to 1 kg), the energy demand for the activities practised in the house can be calculated.

For the shower timetable, every occupant has to provide information about the average time spent in the shower and usual time he is taking showers or baths at. The Figureb9 below shows an example of the shower timetable, filled for one of the occupant of the house. If the user specifies the value “1 shower”, the cell will automatically turn blue for clarification purposes.

Peter

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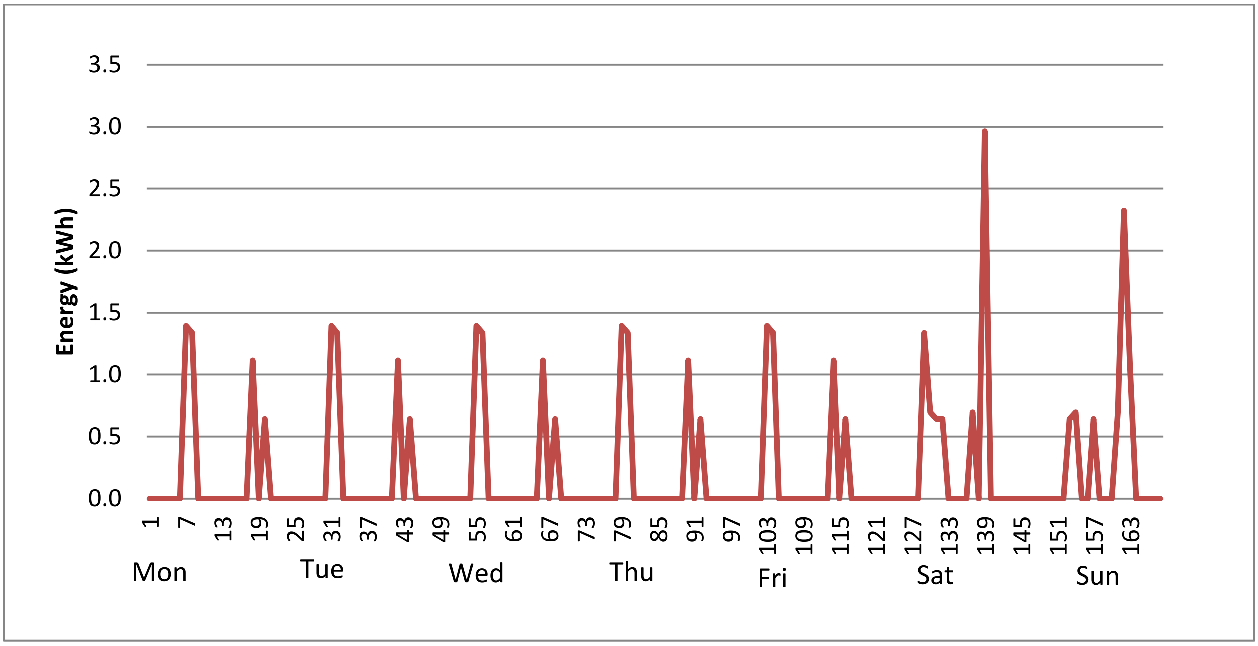
Average time in the shower (min)	Volume of water used for showers (L)
5	24

Shower Schedule	Monday Bath	Monday Showers	Tuesday Bath	Tuesday Showers
1am	No bath	No shower (No shower / 1 shower)	No bath	No shower
2am	No bath		No bath	No shower
3am	No bath	No shower	No bath	No shower
4am	No bath	No shower	No bath	No shower
5am	No bath	No shower	No bath	No shower
6am	No bath	No shower	No bath	No shower
7am	No bath	1 shower	No bath	1 shower

Figureb9-Showers and Bath timetable

Assuming the same cold inlet water temperature of 15 °C and a delivered temperature of 40°C (Energy Saving Trust, 2008)), the energy demand for showers and baths was calculated.

For the example of a family of four considered, the following hot water demand profile was drawn:



Graph 2-Hot water demand profile for a family of 4

In Graph 2, it can be seen that peaks occurs in the morning and at night, around 5pm, 6pm and 8pm respectively. The profile is a bit modified for the weekend as the 4 occupants are present and have more time to do activities in the house, like taking a bath or having a family lunch for example.

It was found that for this hypothetical family of 4, there was an energy consumption of 4.5 kWh/day during the weekdays, 7 kWh/day on the Saturday and 6 kWh/day on the Sunday due to extra cleaning activities and baths. These values make sense when comparing them with the one obtained during a field trial run by The Energy Saving Trust. Actually this study found that the mean energy content for DHW is 16.8 ± 2.2 MJ/day which correspond to 4.7 ± 0.7 kWh/day (Energy Saving Trust, 2008).

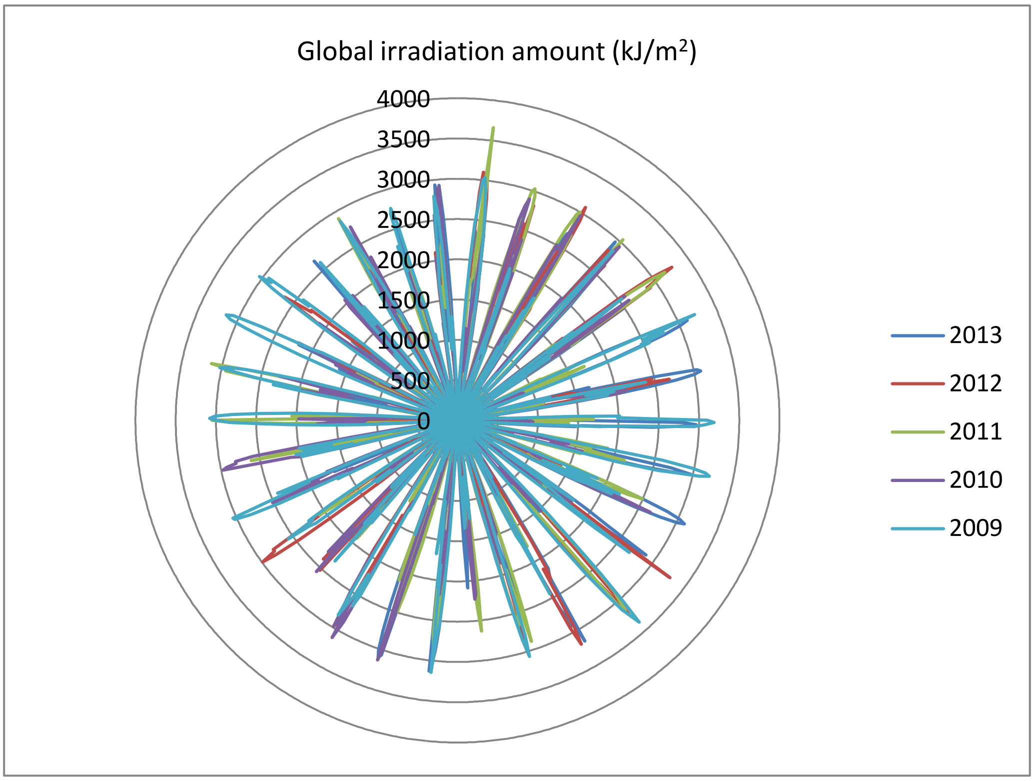
A way of acquiring a personalised demand profile, based on user specifications was explained. The weather forecast acquisition and calculation will now be described.

3.3. Weather forecast

It was willing to use weather forecast in order to be able to predict the energy contribution from the renewable sources to the water tank. A lot of different weather predictions are available on the Internet and it was agreed to use this mean to acquire them. However free solar radiation forecasts are not to be found freely on the Web, so a methodology to predict it was undertaken. It was decided to:

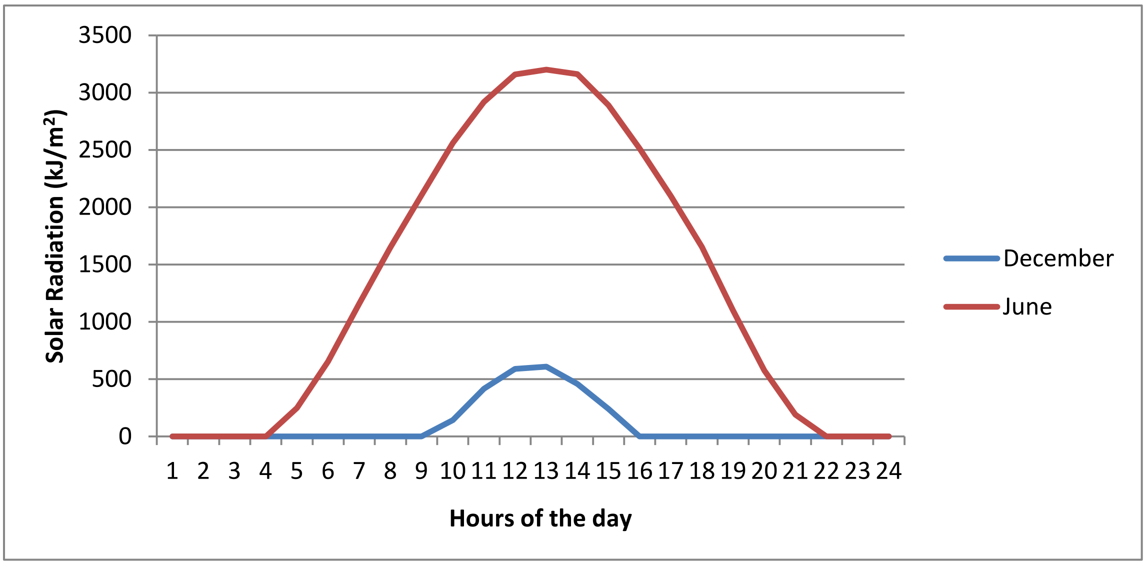
- Find historical data for solar radiation.
- Obtain a maximum hourly value of solar radiation, for each month of the year.
- Predict the solar radiation by using cloud forecast, available on the Internet, and considering that a 0% cloud forecast would correspond to the maximum solar radiation value found before.

First, data from previous year were collected. The British Atmospheric Data Centre (BADC) makes available historical data from MetOffice, from different weather station around the UK. For this precise project, the location was set to Kinloss, which is the nearest MetOffice station from the Findhorn community. The only available and usable data from the BADC was the global solar irradiation amount, in kJ/m^2. This correspond to « the total solar radiation flux from the whole sky (from UV to near infra-red) - measured using a pyranometer mounted horizontally, facing upwards » (British Atmospheric Data Centre, 2014). This horizontal radiation data was given hourly and, because there was some missing, replicated or senseless values, a big work of cleaning and management has to be undertaken. Finally, the horizontal solar radiations for each hour of the years over the 5 past years were found. It was decided to classify them by month and the following graph could be drawn, showing the solar radiation measurement for the example of the month of June:



Graph 3-Hourly global solar irradiation amount for the month of June

This data were then arranged hourly in order to find the maximum solar radiation for each hour of each month. However this value was not just taken as the maximum hourly quantity but as an average of the ten maximum one in order to give more precision. For example for 11 am in June it was found that the maximum calculated radiation was 2919 kJ/m^2. The following graph is showing the maximum solar radiation values, S_{max}, for June and December, for the different hours of the day:



Graph 4- Maximum Solar radiation values for June and December.

The next step was to extract weather data from the Internet and put them in Excel so they can be used in the algorithm. The functionalities of the macro with the VBA language were used in Excel in order to automatically extract the web data and put them in the model to run the algorithm when the user clicks on a button. This data is taken from AccuWeather.com and gives the percentage of cloud forecast for the next 24 hours.

By considering that 0% of cloud corresponds to the previously calculated maximum radiation S_{max}, it is possible to calculate the predicted radiation for the next 24 hours by using the simple formula below:

$S_{hor} = S_{max} \times (1 - c_f)$, where S_{hor} is the resulted available horizontal radiation in kJ/m^2

S_{max} is the maximum horizontal radiation in kJ/m^2

c_f is the forecasted percentage of cloud

The Figure 10 below illustrates what the programme can achieve with an example of a particular weather prediction. An arbitrary prediction for the next 6 hours of one randomly chosen day was put into the Excel model and the result are presented below:

21st of July

Web forecast

Next hours	Predicted % of cloud
7 am	0.1
8am	0.46
9am	0.68
10am	0.89
11am	0.6
12am	0.34

Historical data

Next hours	Max. Solar radiation [kJ/m^2]
7 am	1022.6
8am	1510.8
9am	1971.2
10am	2427.4
11am	2750.3
12am	3013.1

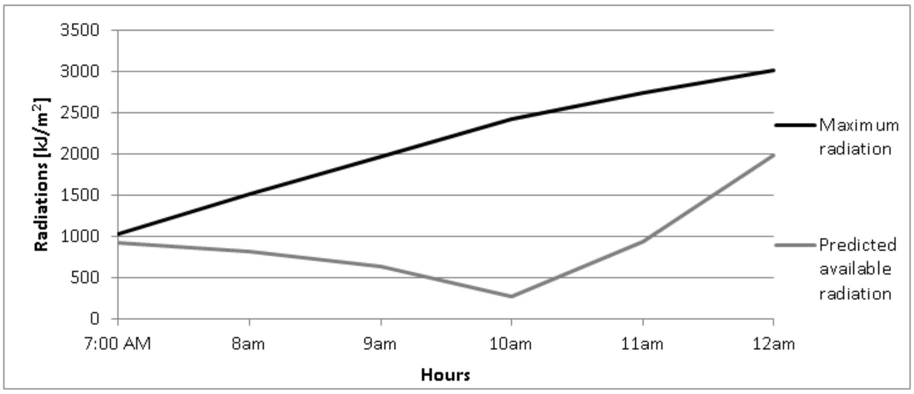


Figure 10- Solar radiation prediction example

In Figure 10, hypothetical cloud forecasts are given for the 21st of July. In the Excel program, the user can specify any date or time, but the default one will be the day and time given by the computer (present's conditions). The program will then identified the month and the hour and look for the maximum hourly solar radiation for this particular situation. The predicted radiation will then be found from the cloud forecast. In the example shown in Figure10, it can be seen that is quite sunny at 7am then it turns cloudy before going sunny again. In the Graph, this variation can be observed for the predicted radiation which first has a negative slope before going up and becoming closer to the maximum radiation.

Other weather data from MetOffice showing the predicted wind speeds and directions can also be extracted from the web with the Excel programme. This was done in case it was willing to try to charge the hot water storage tank when the wind was blowing and when there consequently was some electricity available from the wind turbine. However these data were not used in this project but could be utilised in a future work. Data for the predicted external temperature are also available and could be used for constructing regression analysis models (see section 5.1. Multiple regressions analysis models).

The sun radiation forecast was imported from the Internet to Excel and was now usable to predict the hot water production over the next 24 hours.

3.4. **Hot water production**

The hot water production from the solar system depends on the quantity of solar radiation that reach the collector and on the performances of the system. In order to give a valuable profile for the hot water production, equations that give the energy supply to the water tank from the solar radiation were used.

First, the predicted available solar radiation calculated in the above section is a horizontal radiation and it needs to be transformed into the radiation on a tilted surface. This is a geometry problem that takes account for different angles, including some characteristics angle specific to solar calculations. PVEducation.org proposes a method to translate the global horizontal solar radiation (S_{hor}) into the incident radiation on a tilted surface, here the thermal panel (S_{panel}). This technique is purely geometrical and does not consider any principles that are specific to PV applications. It can be applied for any tilted surface and is therefore valid for a thermal panel.

The method from PVEducation.org uses the equations below, here adapted for the case studied. The Figure11 is showing the configuration analysed with the different values and terms utilised through the calculations.

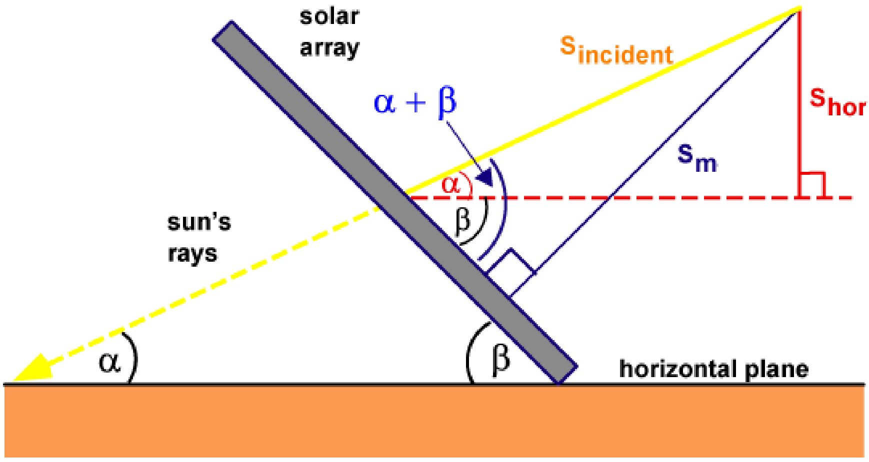


Figure 11 – Solar radiation calculations

Source (PVEducation.org, 2014)

$S_{panel} = \frac{S_{hor} \times \sin(\alpha+\beta)}{\sin \alpha}$, where S_{panel} is the incident radiation on the panel in kJ/m^2

S_{hor} is the previously calculated horizontal radiation in kJ/m^2

β is the tilt angle (°) of the panel measured from the horizontal

α is the solar altitude in °

The solar altitude is the angular height of the sun in the sky measured from the horizontal. It is a complex variable that depends on the site latitude ϕ, the solar declination angle δ and the hour angle θ_h. It can be expressed with the following equation:

$$\alpha = \sin^{-1}(\cos\phi \cos\delta \cos\theta_h + \sin\phi \sin d)$$

(ESRU, 2013) (PVEducation.org, 2014)

The solar declination angle δ is equal to:

$$\delta = 23.45 \times \sin\left[\frac{360}{365} \times (d - 81)\right]$$, d is the day of the year.

(ESRU, 2013) (PVEducation.org, 2014)

The hour angle θ_h converts the local solar time into the number of degrees which correspond to the movement of the sun across the sky. The hour angle is equal to 0° at solar noon is negative in the morning and is positive in the afternoon. It is equal to:

$\theta_h = 15 \times (12 - t_s)$ where t_s is the local solar time which is a time scale that relates to the apparent angular motion of the sun across the sky vault.

(ESRU, 2013) (PVEducation.org, 2014)

Solar time is not essentially equal to the clock time (or local mean time) t_m and a correction need to be applied to the standard time to find the solar one:

$t_s = t_m + \frac{4L+e_t}{60}$ where t_m is the local mean time which in UK is known as Greenwich Mean Time (GMT)

e_t is the equation of time in minutes

L is the longitude difference in °

(ESRU, 2013) (PVEducation.org, 2014)

The longitude difference is the difference between an observer's actual longitude and the longitude of the mean or reference meridian for the local time zone (ESRU, 2013). For the UK, the reference meridian is at 0° so the L to consider in the equation for this case is just the longitude of the UK site where the panel is installed.

The equation of time is an empirical equation that corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt and that can be seen below:

$$e_t = 9.87 \sin\big(1.9726(d-81)\big) - 7.53 \cos\big(0.9863(d-81)\big) - 1.5 \sin\big(0.9863(d-81)\big)$$

where d is the day of the year.

(ESRU, 2013) (PVEducation.org, 2014)

These equation were put in Excel and are solved each time that the algorithm is run. The program can find the day of the year and clock time (actual time and 24 next hours) and therefore can calculate the predicted radiation on the panel, from the horizontal one previously evaluated. Some issues were found regarding these calculations as it was seen that if the solar altitude was reduced to small values the tilted radiation become senselessly big. This case was mostly occurring at sunset and it was thought that the sun should be too low to provide energy to the system (but it was making sense with the fact that there would be small altitude angle for this period of the day). It was decided to set the tilted radiation to 0 whenever the solar altitude was below 0.15 radians (this value was identified after trying different day of the year). It was seen that a simplified equation could be used to estimate the solar altitude. However the model was not adapted to this new equation as there was not enough time and that the complex model usually works well and should give more precise values than the one given with the simplified equation.

The tilted radiation need to be modified, as the collector is not a perfect exchanger and will not be able to absorb all the energy that reaches it. Further calculations were performed in order to find out what will be the solar input to the hot water system depending on the solar radiation on the collector. The calculations used are from the Standard Assessment Procedure (SAP), Appendix H and are the following:

$$\mathrm{Qs} = \mathrm{S_{panel}} \times \mathrm{Z_{panel}} \times \mathrm{A_{ap}} \times \mathrm{h_0} \times \mathrm{UF} \times \mathrm{f1} \times \mathrm{f2}$$

where Qs is the solar input in kWh

S_{panel} is the total solar radiation on collector in kWh/m², calculated just before.

Z_{panel} is the over shading factor for the solar panel. The program created in Excel is using SAP assumptions and audit specifications to calculate it.

A_{ap} is aperture area of collector in m² obtained during the audit.

h_0 is the zero-loss collector efficiency given in technical data of collectors, and being collected during the auditing work.

UF is the utilisation factor calculated in the program using SAP method.

f_1 is the collector performance factor

f_2 is the solar storage volume factor

The collector performance and the solar storage volume factors, f_1 and f_2 respectively are estimated using the equations below:

$$f_1 = 0.97 - 0.0367\left(\frac{a_1}{h_0}\right) + 0.0006\left(\frac{a_1}{h_0}\right)^2 \quad \text{if } \frac{a_1}{h_0} < 20$$

$$f_1 = 0.693 - 0.0108 \times \left(\frac{a_1}{h_0}\right) \quad \text{if } \frac{a_1}{h_0} \gg 20$$

,a_1 is the linear heat loss coefficient of the collector in W/m²K, given in technical data of collectors, and being collected during the auditing work.

$$f_2 = 1.0 + 0.2 \times \ln\left(\frac{V_{eff}}{V_d}\right) \text{ subject to } f\left(\frac{V_{eff}}{V_d}\right) \ll 1.0$$

V_{eff} is the effective solar volume in litres.

Vd is the daily hot water demand in litres.

In the case of a combined cylinder, as considered, the effective solar volume V_{eff} is the volume of the dedicated solar storage plus 0.3 times the volume of the remainder of the cylinder. In this project, as not precise value of were found for the ROTEX Sanicube, it was assumed that the volume dedicated for the solar storage was one third of the storage tank.

Once the solar input was determined, the temperature of the solar input T_{sol-in} was estimated by using the formula below:

$$T_{sol-in} = \left(\left(\frac{Q_s \times 3600}{\dot{m} \times c_p \times t}\right) + T_6 + 273\right) - 273$$

, where T_{sol-in} is the solar temperature entering the storage tank, in °C.

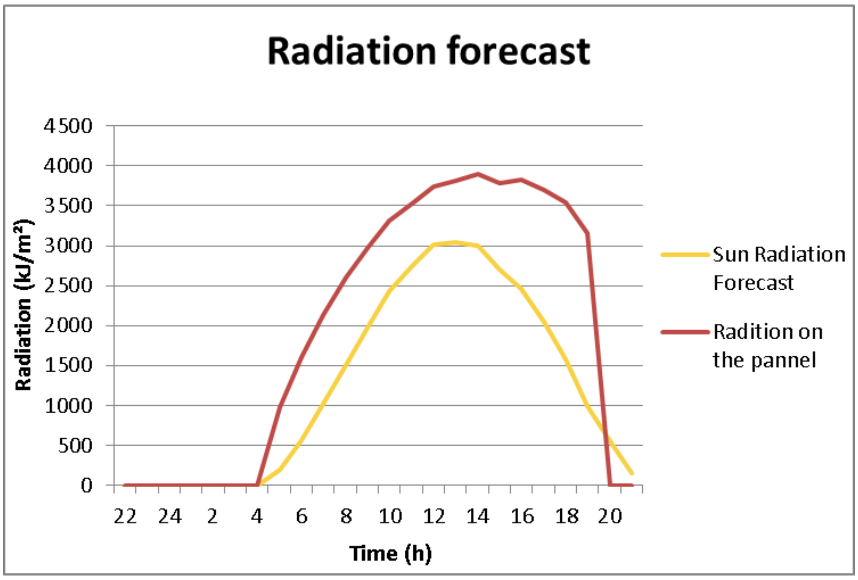
Q_s is the solar input in kWh

c_p in the heat capacity of the working fluid used by the collector. In the case studied, the collector used the 100% tyfocor antifreeze mixture which as a heat capacity of 2.6 kJ/(kgK) at 50 °C (Resol, 2009). This value was assumed constant.

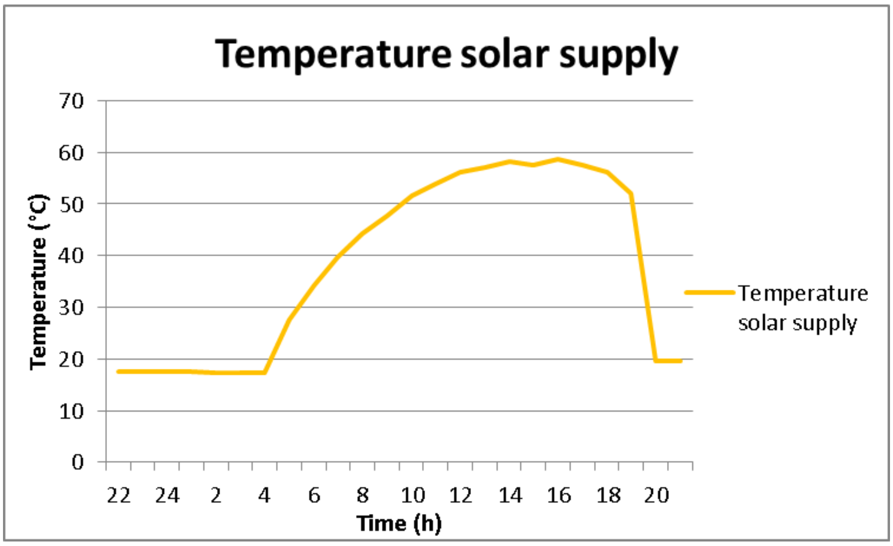
T_6 is the tank bottom temperature that is assumed to be equals to the solar return temperature $T_{sol-out}$.

$\dot{m}$ is the mass flow running from the collector to the storage tank, in kg/s. The specifications for the collector usually give the flow rate. In the case study, the working fluid has a mass flow of 0.5 litres per square metre of collector area per minute. The density is used to transform this flow rate in mass flow, and is assumed to be a constant value of 1.054 kg/l (Resol, 2009).

The graphs below show how the temperature of the solar supply changes with the available sun radiation:



Graph 5- Sun Radiation forecast

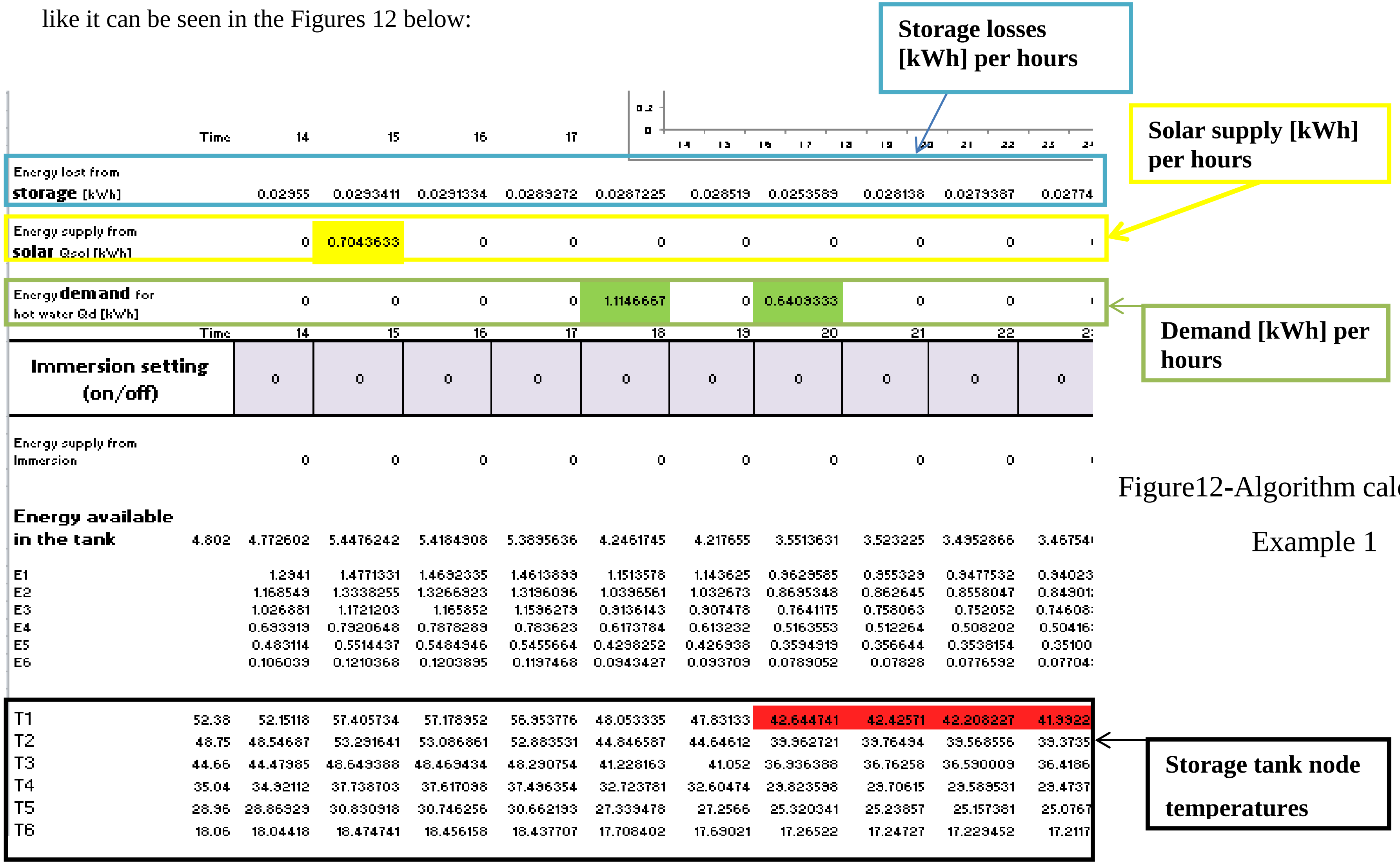


Graph 6- Temperature of the solar supply

These solar calculations would be an input to express the overall results and outputs of the models. These are explained below.

3.1. System Model Calculations and Back-up settings

Calculations were made in order to find the temperatures in the tank every hour, for the next 24 hours. It was first based on energy calculations like it can be seen in the Figures 12 below:



	Time	14	15	16	17	18	19	20	21	22	2:
Energy lost from **storage** [kWh]		0.02955	0.0293411	0.0291334	0.0289272	0.0287225	0.028519	0.0253589	0.028138	0.0279387	0.02774
Energy supply from **solar** Qsol [kWh]		0	0.7043633	0	0	0	0	0	0	0	[illegible]
Energy **demand** for hot water Qd [kWh]		0	0	0	0	1.1146667	0	0.6409333	0	0	[illegible]
Immersion setting (on/off)		0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	0	[illegible]
Energy available in the tank	4.802	4.772602	5.4476242	5.4184908	5.3895636	4.2461745	4.217655	3.5513631	3.523225	3.4952866	3.46754
E1		1.2941	1.4771331	1.4692335	1.4613899	1.1513578	1.143625	0.9629585	0.955329	0.9477532	0.94023
E2		1.168549	1.3338255	1.3266923	1.3196096	1.0396561	1.032673	0.8695348	0.862645	0.8558047	0.84901
E3		1.026881	1.1721203	1.165852	1.1596279	0.9136143	0.907478	0.7641175	0.758063	0.752052	0.74608
E4		0.693919	0.7920648	0.7878289	0.783623	0.6173784	0.613232	0.5163553	0.512264	0.508202	0.50416
E5		0.483114	0.5514437	0.5484946	0.5455664	0.4298252	0.426938	0.3594919	0.356644	0.3538154	0.35100
E6		0.106039	0.1210368	0.1203895	0.1197468	0.0943427	0.093709	0.0789052	0.07828	0.0776592	0.07704
T1	52.38	52.15118	57.405734	57.178952	56.953776	48.053335	47.83133	42.644741	42.42571	42.208227	41.9922
T2	48.75	48.54687	53.291641	53.086861	52.883531	44.846587	44.64612	39.962721	39.76494	39.568556	39.3735
T3	44.66	44.47985	48.649388	48.469434	48.290754	41.228163	41.052	36.936388	36.76258	36.590009	36.4186
T4	35.04	34.92112	37.738703	37.617098	37.496354	32.723781	32.60474	29.823598	29.70615	29.589531	29.4737
T5	28.96	28.86929	30.830918	30.746256	30.662193	27.339478	27.2566	25.320341	25.23857	25.157381	25.0767
T6	18.06	18.04418	18.474741	18.456158	18.437707	17.708402	17.69021	17.26522	17.24727	17.229452	17.2117

Figure12-Algorithm calculations:

Example 1

From the above figure, it can be seen that the storage losses, the solar supply and the demand are given in kWh for every hour. The storage losses occur each hour, however for the solar supply and the demand the value will be highlight in yellow and green respectively, whenever it is different to zero.

The solar supply is assumed to occur only if the difference between the temperatures of the solar supply with the temperature of the node 3 of the storage tank (node at which the solar energy will be supply) is positive. If it is negative it is presumed that the solar pump will not let the working fluid circulated as the solar energy is not high enough to offer a gain to the system.

The energy demand comes from the profile explained in an above section.

The storage tank node temperatures are also shown in the results. Data from the Findhorn Centini's house were taken as an initial system for the tank temperature. As the Centini houses do not have a direct stratified tank some small modifications to this data were assumed in order to have the system required. The temperature defined gave an initial state of the system that would be taken as a reference. The energy content for each node was calculated using the formula below:

$Q_{(\text{node})} = \frac{\text{m}\times\text{Cp}\times(\text{T}_{node}-T_{cold})}{3600}$, where $Q_{(\text{node})}$ is the energy present in the node in kWh .

m is the mass of water present in one node considered in kg.

c_p is the heat capacity of the water, here assumed constant, with a value of 4180 J/kgK.

T_{node} is the node temperature in °C.

T_{cold} is the cold temperature.

This energy content is then translated into a percentage compared to the overall energy available in the tank. It is supposed that the tank is stratified and that this percentage is constant through time. This assumption features the fact that the relationship between the nodes is not considered. It was assumed that the percentage of energy for each node were the followings:

Table 1: Node energy content in relation to the total energy available in the tank

Nodes	% of energy content
Top Node	27.1%
Node 2	24.5%
Node 3	21.5%
Node 4	14.5%
Node 5	10.1%
Bottom Node	2.2%

The top node temperature T_1 is shown in red in Figure 12 if it becomes inferior to 45°C. Actually it was supposed that this temperature is a limit and below it the water is not warm enough to supply the demand and needs to be heated. This top temperature will be highlight in yellow if it is increased above 80°C as this high temperature could damage the storage tank. The Excel program will automatically turn this cells into the appropriate colour when one of the above situation occurs.

The solar fraction, that show the portion of hot water supply by the solar system compared to the role played by the back-up heater was also calculated, using the following formula:

$SF = \frac{E_{solar}}{E_{solar}+E_{Auxiliary}}$, where E_{solar} is the energy provided by the solar system

$E_{Auxiliary}$ is the energy provided by the auxiliary system

In Figure 12, the immersion heater settings are fixed to 0 which mean that the device is OFF. In the following example presented below, this setting is changed to 1 (immersion ON for the entire hour) at a chosen time, in order to be able to provide a suitable hot water temperature to meet the demand:

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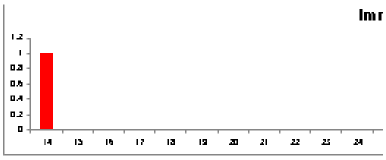


Time		14	15	16	17	18	19	20	21	22	23	
Energy lost from storage [kWh]		0.1368065	0.135192688	0.13359795	0.132022019	0.13046468	0.12892571	0.11370836	0.12606359	0.124576533	0.12310702	0
Energy supply from solar Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	
Energy demand for hot water Qd [kWh]		0	0	0	0	1.11466667	0	0.64093333	0	0	0	
Time		14	15	16	17	18	19	20	21	22	23	
Immersion setting (on/off)		1	0	0	0	0	0	0	0	0	0	
Energy supply from Immersion		2.4	0	0	0	0	0	0	0	0	0	
Energy available in the tank	13.339	15.602505	15.46731242	15.3337145	15.20169245	13.9565611	13.8276354	13.0729937	12.9469301	12.82235358	12.6992466	1
E1		4.2306473	4.193989529	4.15776421	4.121966198	3.7843466	3.74938816	3.54476571	3.51058334	3.476804191	3.4434235	3.
E2		3.820201	3.787099689	3.75438885	3.722063873	3.41719924	3.38563238	3.20086186	3.16999577	3.139493788	3.1093516	3.
E3		3.3570623	3.327973992	3.29922882	3.270822736	3.0029181	2.97517822	2.81280819	2.78568413	2.758880022	2.7323921	2
E4		2.2685477	2.24889114	2.22946648	2.21027096	2.02923338	2.01048805	1.90076588	1.88243669	1.864323716	1.8464244	1.
E5		1.5793862	1.565701106	1.55217746	1.53881334	1.41277312	1.39972242	1.32333272	1.31057176	1.297961315	1.28549963	1
E6		0.3466607	0.343656959	0.34068864	0.337755342	0.31009068	0.30722617	0.29045933	0.28765842	0.284890543	0.28215532	0.
T1	52.381	58.723436	58.34458078	57.9701947	57.60022482	54.1109505	53.7496575	51.6348992	51.2816269	50.93252178	50.5875347	!
T2	48.755	54.481503	54.13940349	53.8013393	53.46726299	50.3165089	49.9902676	48.0806776	47.7616788	47.44644297	47.1349257	46
T3	44.662	49.694998	49.39437236	49.0972931	48.80371822	46.034943	45.7482533	44.0701707	43.7898455	43.51282702	43.2390762	42
T4	35.044	38.445277	38.24212853	38.0413761	37.84299174	35.9719813	35.7782497	34.644279	34.4548481	34.2676518	34.0826637	33
T5	28.955	31.322843	31.18140856	31.0416426	30.90352543	29.6009088	29.4660308	28.6765487	28.544665	28.41433704	28.2855464	2:
T6	18.063	18.582714	18.55167001	18.5209927	18.49067722	18.2047649	18.1751604	18.0018764	17.9729291	17.94432332	17.916055	1'

Figure 13- Algorithm calculations: Example 2

In Figure 13, it can be seen that the immersion heater is ON and in consequence, the tank top temperature is not falling below 45°C and is not appearing in red. However the solar energy that was available and outlined in yellow in Figure 12 is not here anymore. Actually, in this case, the backup system has heated the tank at such a temperature that the solar energy became unusable. The immersion settings need to be completed by the user for the moment and should be automatically decided by the controller in a practical implementation.

As soon as the calculations are finished and the control settings are defined, a general overview is accessible to the user so it can have feedback. This is presented as the model outputs below.

3.2. Model Outputs

The algorithm is finally outputting the result in a fashion that can be seen in Figure14 below. Information about demand prediction, solar prediction and node temperatures are given, along with the times at which the immersion heating is ON, the predicted solar fraction and the cost relative to the control chosen. The cost was calculated using off peak and peak rates. The off peak tariff was assign for times between 12-midnight and 7am and had a value of 7.09 pence/kWh while the peak tariff was set as 13.52 pence/kWh (Energy Saving Trust, 2014).

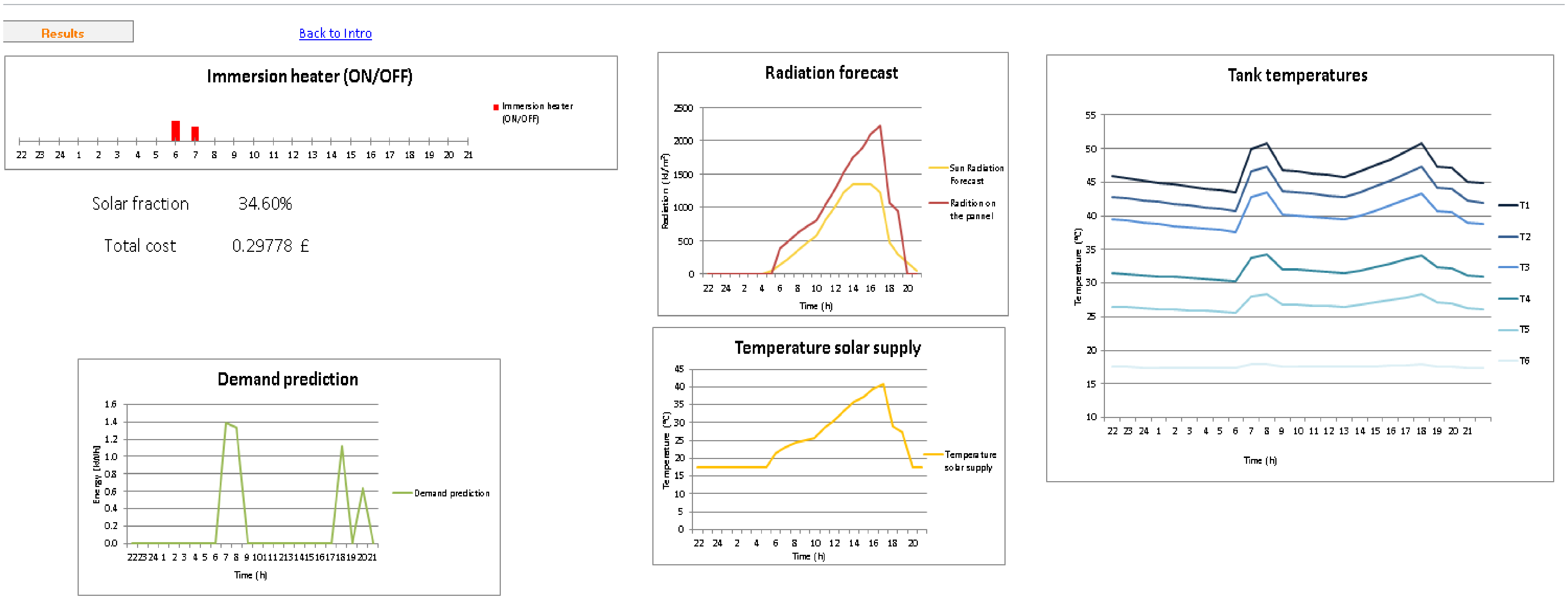


Figure 14-Output Result from the Algorithm

The construction of the algorithm has been explain and it assumptions has been outlined. The way to run it have been defined, and complementary instruction can be found in the Excel spread sheet. The next section will present results found from this model.

4. Results and Analysis

Results for different weather and different level of charge of the hot water storage tank were calculated for the SDHW system presented in the above sections. The algorithm was run from 10 pm, which mean that the storage losses, the hot water demand, the solar supply and the tank nodes temperatures were predicted for the entire following day, until 9pm. Different weather scenarios were examined for diverse period of the year:

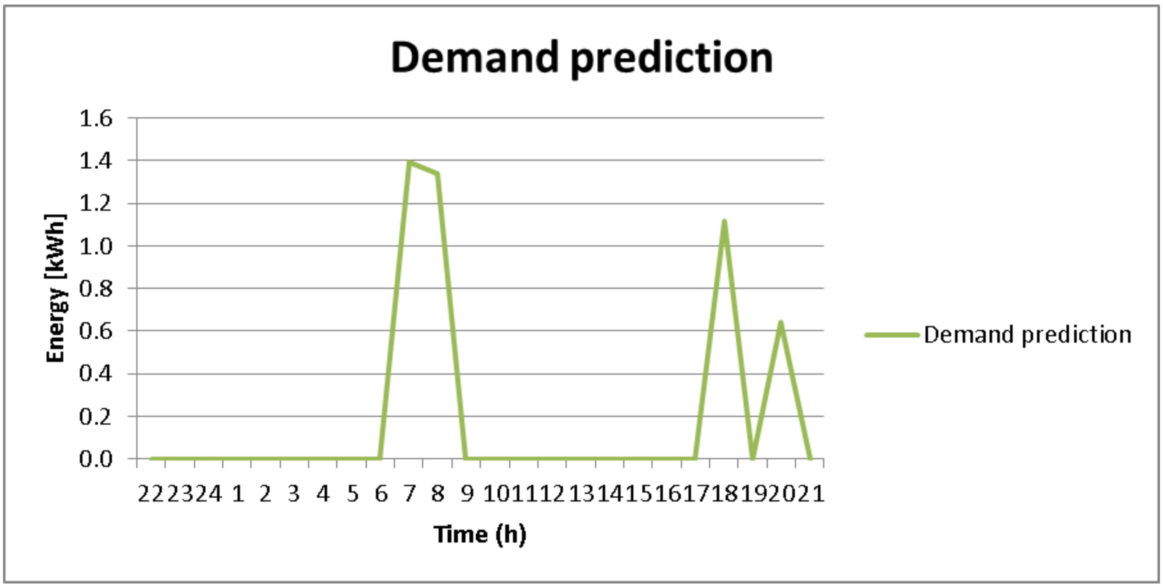
- Sunny day, which corresponds to weather forecast of 0% of clouds.
- Partially sunny day, which corresponds to weather forecast of 50% of clouds.
- Cloudy day, which corresponds to a weather forecast of 100% of clouds

Three levels of charge for the tank were set:

- Fully discharged: the top temperature of the tank is 45.9°C.
- Partially charged: the top temperature is 52.4°C.
- Fully charged: the top temperature of the tank is 78.9°C.

Results were found for this three weather forecasts and levels of charge and conclusions drawn regarding the use of the immersion heater.

The demand prediction for the next day can be seen below:



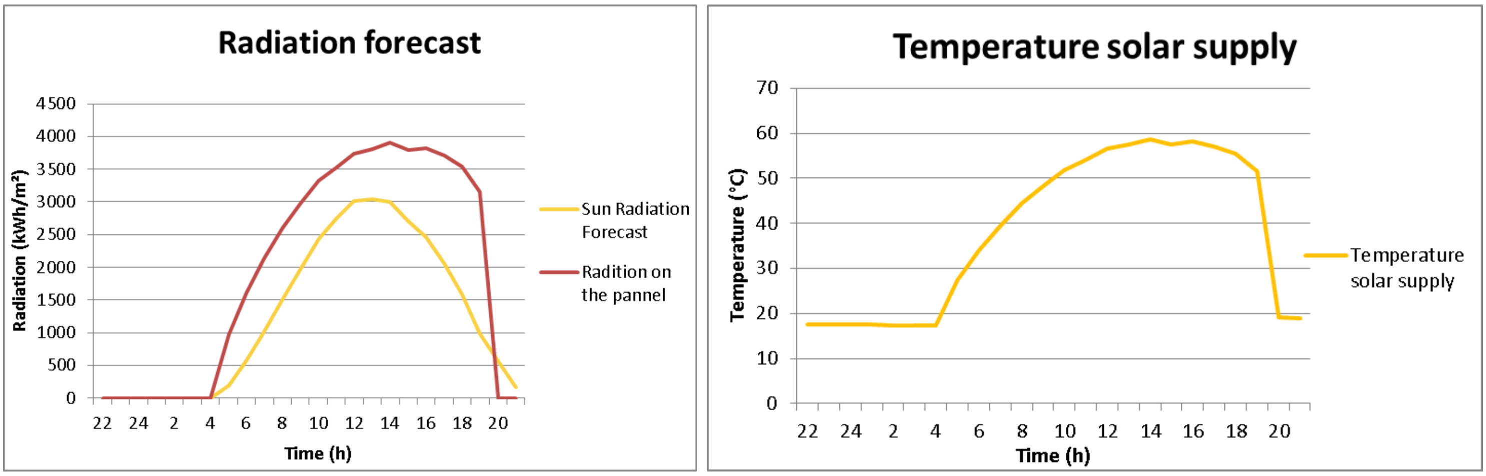
Graph 7- Demand prediction

The simulations were first run for a summer day, the 20th of July and the results below were found.

4.1. Summer simulation

Scenario 1: Sunny day, 0% cloud forecast.

For a sunny day, the weather and solar input predictions are shown below:



Graph 8-Weather and solar forecasts for a 0% cloud prediction in summer

From the above graphs, it can be seen that a large amount of solar radiation is available. The solar supply temperature almost reaches 60°C between 12-noon and 5pm and is above 30°C from 6am until 7 pm.

If the tank is fully discharged, the Figure 15 below is found:

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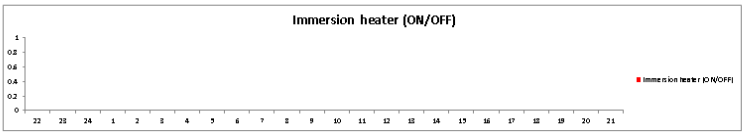

6

Time		22	23	24	1	2	3	4	5	6	7	8
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0.37742963	0.4996527	0.60843509
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	10.463366	9.471256	8.64482267
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	44.32185	41.541626	39.2256835
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	41.4771212	38.966627	36.8753713
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	38.2671907	36.061054	34.2233299
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	30.722893	29.232088	27.9902387
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	25.9464396	24.908526	24.0439375
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.4026426	17.17483	16.9850609
Solar fraction		1										

Time	9	10	11	12	13	14	15	16	17	18	19	20	21
Energy lost from **storage** [kWh]	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]	0.69395248	0.7765147	0.8256324	0.87522843	0.8912246	0.91297733	0.88659085	0.89461059	0.866087	0.82769637	0.73943802	0	0
Energy **demand** for hot water Qd [kWh]	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
Immersion setting (ON = 1/ OFF = 0)	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	9.25635067	9.9377167	10.669323	11.451634	12.251037	13.0732767	13.8701999	14.6762005	15.45472	15.0812212	15.7351482	15.0097125	14.9262069
T1	40.9393894	42.848805	44.89901	47.0913071	49.331503	51.6356923	53.8689375	56.1276208	58.3093	57.2626241	59.0951461	57.0622327	56.8282222
T2	38.422818	40.146987	41.998286	43.9778929	46.000751	48.0813937	50.0979754	52.1375271	54.10755	53.1624154	54.8171509	52.9814655	52.7701581
T3	35.5831733	37.098314	38.725173	40.4647835	42.242402	44.0708001	45.8429032	47.6351917	49.36638	48.5358285	49.9899537	48.3768159	48.1911262
T4	28.909158	29.93302	31.032376	32.2079248	33.409157	34.6447042	35.8422097	37.0533555	38.22321	37.6619643	38.6445949	37.5545109	37.4290303
T5	24.6836986	25.396522	26.161905	26.9803339	27.816644	28.6768448	29.5105604	30.3537726	31.16824	30.7774922	31.4616098	30.7026821	30.6153212
T6	17.1254826	17.281941	17.449935	17.6295729	17.813135	18.0019414	18.1849342	18.3700115	18.54878	18.4630141	18.6131716	18.446594	18.4274191

Figure 15 -Fully discharged tank on a sunny summer day with no immersion heater

From Figure 15, it can be observed that the energy supplied by the solar system is available from 7am until 6pm. The total solar energy available through the day is equal to 10.7 kWh, and this is enough to cope with the evening hot water demand; however as the storage tank is discharged in the morning, there is a need for the immersion heater to turn on and supply the necessary energy to match the morning hot water demand.

A suggested setting found for the auxiliary heater is shown below:

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Time 22 23 24 1 16 17 18 19 20 21

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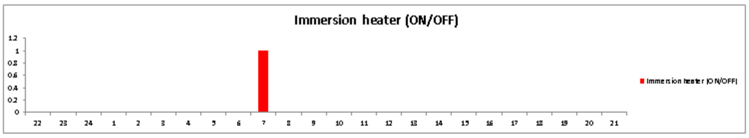


Time		22	23	24	1	2	3	4	5	6	7	8
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0.37742963	0.4996527	0.60843509
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	0	1	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	0	2.4	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	10.463366	11.871256	11.0448227
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	44.32185	48.267228	45.9512859
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	41.4771212	45.039729	42.9484735
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	38.2671907	41.397889	39.5601649
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	30.722893	32.838474	31.5966253
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	25.9464396	27.419329	26.5547409
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.4026426	17.725928	17.5361591
Solar fraction		0.81645										

Time	9	10	11	12	13	14	15	16	17	18	19	20	21
Energy lost from **storage** [kWh]	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]	0.69395248	0.7765147	0.8256324	0.87522843	0.8912246	0.91297733	0.88659085	0.89461059	0.866087	0.82769637	0.73943802	0	0
Energy **demand** for hot water Qd [kWh]	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
Immersion setting (ON = 1/ OFF = 0)	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.6563507	12.337717	13.069323	13.851634	14.651037	15.4732767	16.2701999	17.0762005	17.85472	17.4812212	18.1351482	17.4097125	17.3262069
T1	47.6649918	49.574407	51.624612	53.8169096	56.057105	58.3612947	60.5945399	62.8532232	65.0349	63.9882265	65.8207485	63.7878352	63.5538247
T2	44.4959202	46.220089	48.071388	50.050995	52.073853	54.1544959	56.1710775	58.2106293	60.18065	59.2355175	60.8902531	59.0545676	58.8432602
T3	40.9200083	42.435149	44.062008	45.8016185	47.579237	49.4076351	51.1797382	52.9720267	54.70321	53.8726635	55.3267886	53.7136509	53.5279612
T4	32.5155446	33.539407	34.638763	35.8143114	37.015544	38.2510909	39.4485963	40.6597421	41.8296	41.2683509	42.2509815	41.1608975	41.035417
T5	27.194502	27.907325	28.672708	29.4911373	30.327448	31.1876482	32.0213638	32.864576	33.67904	33.2882956	33.9724132	33.2134855	33.1261246
T6	17.6765808	17.833039	18.001033	18.1806711	18.364233	18.5530396	18.7360324	18.9211097	19.09988	19.0141123	19.1642698	18.9976922	18.9785173

Figure 16-Fully discharged tank on a sunny summer day with immersion heater

The Figure 16 shows the immersion heater set to run for 1 hours. The auxiliary is starting to run at 7am so that the electricity needed is supplied during off-peak tariffs. Moreover, as sun energy is available, by putting the immersion heater at the same moment than when a hot water demand occurs, there will be a water draw and as a consequence, the bottom of the tank will received some cold water. This will allows lower temperatures in the bottom and the solar energy will be fully harvested.

The results for a sunny day with an initial tank fully discharged are sumarized on the table below:

Table 2-Results for a sunny day, tank fully discharged.

Initial Top Temperature	Final Top Temperature	Immersion heater time	Demand meet at any time?	Solar Fraction	Solar energy input
45.9°C	56.8°C	0	No	100%	10.7 kWh
45.9°C	59.9°C	1h off-peak	Yes	82%	10.7 kWh

The same procedure was undertaken, but starting with the tank partially charged. In this case, it was realised that without immersion heater the quantity of hot water demand needed for the morning could still not be delivered. However, it was observed that the part play by the auxiliary heater could be reduced to fifteen minutes without losing any solar inputs. Therefore the solar fraction was increased to 95%. The results found when the storage tank is partially charged at the initial time are found in Table 3 below:

Table 3- Results for a sunny day, tank partially charged

Initial Top Temperature	Final Top Temperature	Immersion heater time	Demand meet at any time?	Solar Fraction	Solar energy input
52.4°C	61.7°C	0	No	100%	10.7 kWh
52.4°C	63.4°C	15 min off-peak	Yes	95%	10.7 kWh

If the tank is fully charged at its initial state, there is no need to turn the auxiliary heater on and the following results are found:

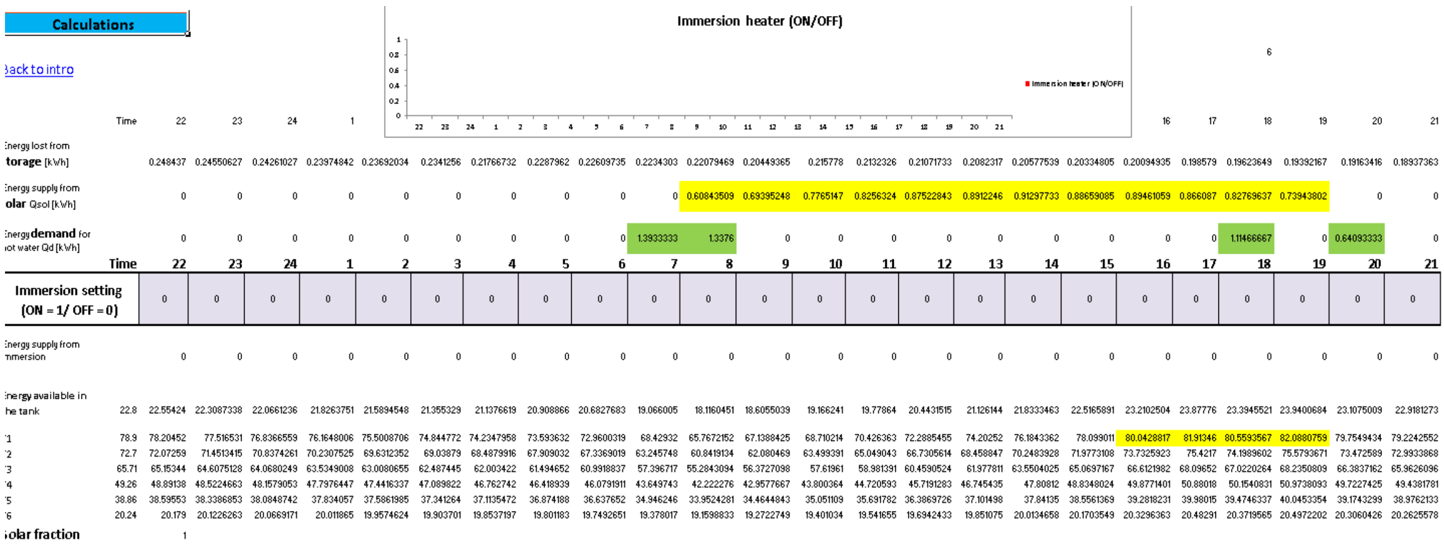


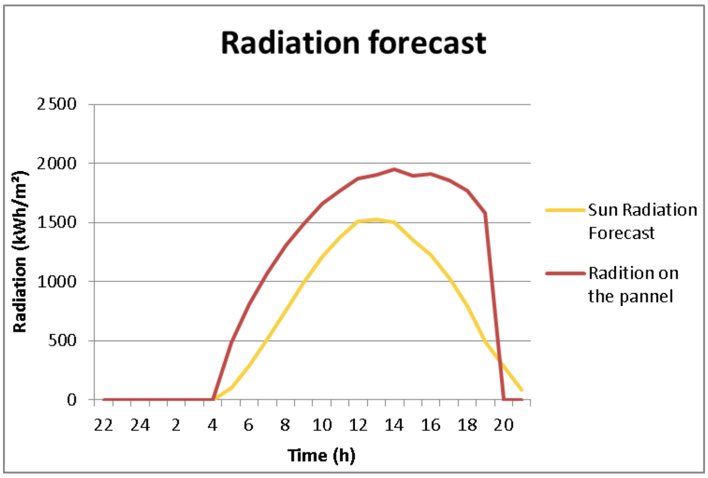
Figure 17-Fully charged tank on a sunny summer day

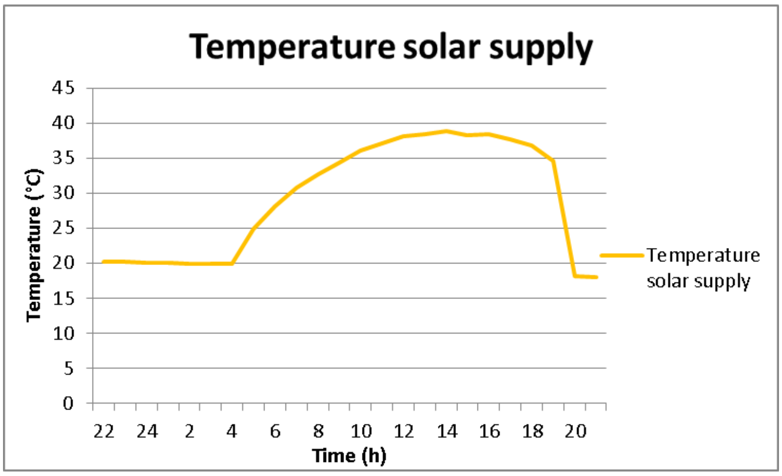
In Figure 17, it can be seen that the tank reaches very high temperatures, above 80 °C. That could be a problem and should lead the solar pump to stop supplying its energy in order to protect the tank. If this happens, some amount of solar energy will be lost.

In the scenario of a sunny summer day, it was realised that the hot water demand could be meet while achieving high solar fraction if the immersion heater is well controlled. Actually, even if the tank is completely discharged, the solar fraction can still be up to more than 82%.

Scenario 2: Partially sunny day, 50% cloud forecast.

For a partially sunny day, the weather and solar input predictions are shown below:

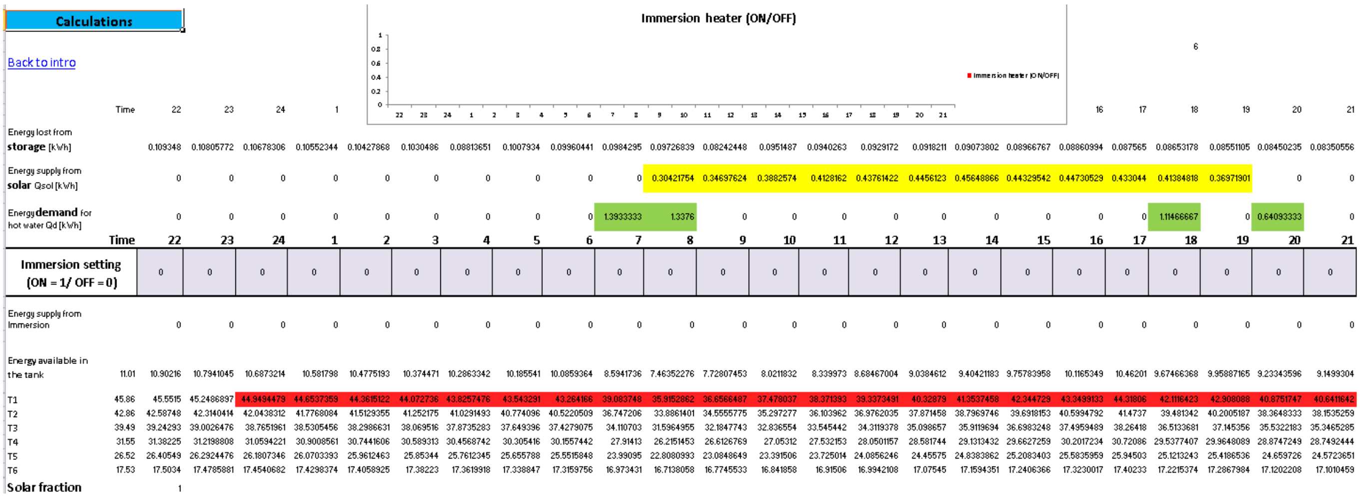




Graph 9-Weather and solar forecasts for a 50% cloud prediction in summer

From the Graph 9, it can be seen that the amount of solar radiation available on the pannel is reduced due to the clouds from almost 4000 kJ/m^2 to less than 2000 kJ/m^2 . The solar supply temperature however still reaches fairly high values, attaining nearly 40°C.

If the tank is fully discharged, and with no use of the immersion heater, the figure below is found:



	Time	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	0.30421754	0.34697624	0.3882574	0.4128162	0.43761422	0.4456123	0.45648866	0.44329542	0.44730529	0.433044	0.41384818	0.36971901	0	0
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
	Time	**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	10.0859364	8.5941736	7.46352276	7.72807453	8.0211832	8.339973	8.68467004	9.0384612	9.40421183	9.75783958	10.1165349	10.46201	9.67466368	9.95887165	9.23343596	9.1499304
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	43.264166	39.083748	35.9152862	36.6566487	37.478037	38.371393	39.3373491	40.32879	41.3537458	42.344729	43.3499133	44.31806	42.1116423	42.908088	40.8751747	40.6411642
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	40.5220509	36.747206	33.8861401	34.5555775	35.297277	36.103962	36.9762035	37.871458	38.7969746	39.6918153	40.5994792	41.4737	39.481342	40.2005187	38.3648333	38.1535259
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	37.4279075	34.110703	31.5964955	32.1847743	32.836554	33.545442	34.3119378	35.098657	35.9119694	36.6983248	37.4959489	38.26418	36.5133681	37.145356	35.5322183	35.3465285
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	30.1557442	27.91413	26.2151453	26.6126769	27.05312	27.532153	28.0501157	28.581744	29.1313432	29.6627259	30.2017234	30.72086	29.5377407	29.9648089	28.8747249	28.7492444
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	25.5515848	23.99095	22.8080993	23.0848649	23.391506	23.725014	24.0856246	24.45575	24.8383862	25.2083403	25.5835959	25.94503	25.1213243	25.4186536	24.659726	24.5723651
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.3159756	16.973431	16.7138058	16.7745533	16.841858	16.91506	16.9942108	17.07545	17.1594351	17.2406366	17.3230017	17.40233	17.2215374	17.2867984	17.1202208	17.1010459
Solar fraction		1																							

Figure 18 -Fully discharged tank on a partially sunny summer day with no immersion heater

From Figure 18, it can be observed that the energy supplied by the solar system is available from 8am until 7pm with is similar as the time interval seen in the previous scenario. It can be observed that however neither the morning nor evening demand are meet. Actually the total solar energy amount provided to the system is only 4.9 kWh, compared to the 10.7kWh from the last situation. That means that the solar input is smaller for each hours and that is why the tank is not warming up enough to meet the evening demand.

A first example of immersion settings is presented in the figure below:

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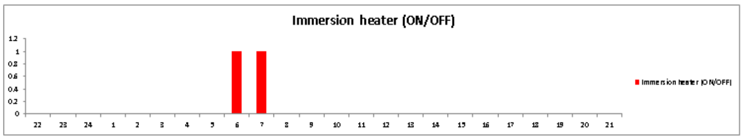


6

Time		22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	0	0.34697624	0.3882574	0.4128162	0.43761422	0.4456123	0.45648866	0.44329542	0.44730529	0.433044	0	0	0	0
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
Time		**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	2.4	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	12.4859364	13.394174	11.9593052	12.223857	12.516966	12.835755	13.1804525	13.534244	13.8999943	14.253622	14.6123174	14.9578	13.756598	13.6710869	12.9456512	12.8621457
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	49.9897684	52.534953	48.5139717	49.2553342	50.076723	50.970078	51.9360347	52.927476	53.9524314	54.9434146	55.9485988	56.91675	53.5505869	53.3109564	51.278043	51.0440325
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	46.5951531	48.89341	45.2625343	45.9319718	46.673671	47.480356	48.3525977	49.247852	50.1733689	51.0682095	51.9758734	52.85009	49.8105103	49.5941281	47.7584427	47.5471352
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	42.7647425	44.784373	41.5936826	42.1819614	42.833742	43.542629	44.3091249	45.095844	45.9091564	46.6955118	47.493136	48.26137	45.5902887	45.4001394	43.7870017	43.601312
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	33.7621308	35.126904	32.9707826	33.3683143	33.808757	34.28779	34.8057531	35.337381	35.8869806	36.4183632	36.9573608	37.4765	35.6715045	35.5430104	34.4529264	34.3274458
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	28.0623881	29.012557	27.5114434	27.788209	28.09485	28.428358	28.7889687	29.159094	29.5417304	29.9116844	30.28694	30.64837	29.3917137	29.3022548	28.5433271	28.4559663
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.8670738	18.075627	17.7461465	17.806894	17.874199	17.947401	18.0265515	18.107791	18.1917758	18.2729773	18.3553424	18.43467	18.1588485	18.1392131	17.9726354	17.9534605
Solar fraction		0.4426																							

Figure 19- Fully discharged tank on a partially sunny summer day with immersion heater

In Figure 19, it can be seen that the demand is meet but as a consequence, a part of the solar energy is lost. Actually, the solar energies that were supplied at 8am, 6pm and 7pm in Figure 18 can no longer be provided as the temperatures are too warm inside the tank. It was thought that if the immersion heater was put ealier in the night , or for an adjusted time, some part of solar input could maybe be utilise. First, it was seen that putting the immersion heater earlier in the nigh was not working as the solar energy lost was quite low, and because the storage losses through the night are not that high, the solar supply temperature would still not be high enough to make the solar pump to turn on. For the settings presented in Figure 19, the solar fraction was 44%.

It was perceived that a better solar fraction could be achieve by running the auxiliary heater for one hour and thirty minutes only. In this way, the solar energy occuring at 6pm, that was no longer available with the previous setting, was now supplied to the system. Therefore, as the part supplied by the immersion heater is reduced and the solar gains are increased, the solar fraction can reach a value of 54%.

The results for a discharged tank on a partially sunny summer are summarised in the table below:

Table 4- Results for a discharged tank on a partially sunny summer

Initial Top Temperature	Final Top Temperature	Immersion heater time	Demand meet at any time?	Solar Fraction	Solar energy input
45.9°C	40.6°C	0	No	100%	4.9 kWh
45.9°C	51.04°C	2h off peak	Yes	44%	3.8 kWh
45.9°C	48.8°C	1h30 off-peak	Yes	54%	4.2kWh

With the immersion heater on for one hour and thirty, the demand can be meet, even though the final top temperature of the tank is quite low but as no significant demand should occurs after 9pm, it is considered as acceptable.

If the tank is partially charged, the solar energy is available from 9am to 7pm with a total amount for the day of 4.6 kWh, with is slightly smaller then if the tank was charged at all. Different settings were tried and a smaal selection of them are reported the table below.

Table 5- Results for a partially charged tank on a partially sunny summer

Initial Top Temperature	Final Top Temperature	Immersion heater time	Demand meet at any time?	Solar Fraction	Solar energy input
52.4°C	44.7°C	0	No	100%	4.6 kWh
52.4°C	49.2°C	1h off peak	Yes	61%	3.8 kWh
52.4°C	48.8°C	45 min off-peak	Yes	70%	4.2kWh

If the controls are well timed, the solar fraction for this situation can reach 70%.

If the tank is fully charged at its initial state, there is no need to turn the auxiliary heater on. However, the solar energy input through the day is reduced to zero as the temperatures inside the tank are too high compared to the temperature that could be provided by the solar system. At the end of the day, the temperature of the tank is still reasonably high, attaining a value of 51.8°C.

In the scenario of a partially sunny day, it was recognise that the hot water demand could be meet with a solar fraction equals to 70% if the storage tank was partially charged. If the tank was discharged, the solar fraction could still be significant (54%) if the appropriate controls were used.

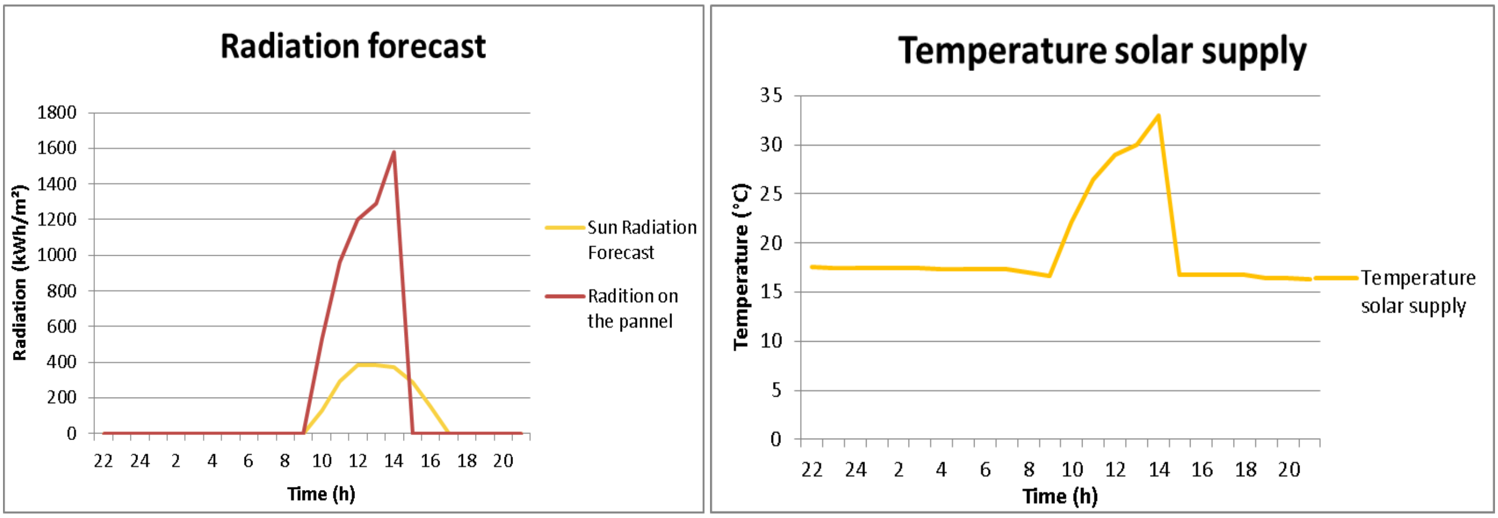
Scenario 3: Cloudy day, 100% cloud forecast.

If there are 100% clouds, there will be a negligible amount of solar radiation available, and for this project it was assumed that in this circumstance, the solar contribution to the system will be zero.

It was seen that if there is no solar input, there would be a need for the immersion heater to be on for 3 hours if the tank is discharged and 2 hours if it is partially charged. This would be done during the night to take advantages of the off peak tariff and of the eventual availability of other renewable energy sources. In both case, the temperatures of the top node of the tank will be very low, around 45°C, at the end of the day. If the tank is fully charged, the system will be in the same situation than in scenario 2, and there will be no need for additional heat.

4.2. Other simulations

Simulations were then run for other periods of the year. An interesting example of how the solar fraction could be improved is shown below. It presents a winter situation (20th of January), with a forecast of 50% clouds. In those circumstances, the weather and solar input predictions are the ones shown in the graphs below.



Graph 10- Weather and solar forecasts for a 50% cloud prediction in winter.

If the storage tank is discharged, the following figure is found:

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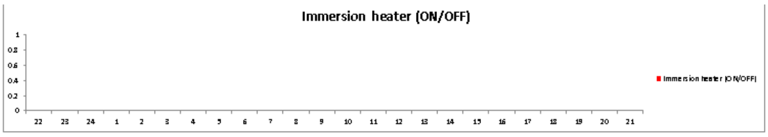

																						6			
	Time	22	23	24	1															16	17	18	19	20	21
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	0	0	0	0.2252312	0.28016208	0.3019359	0.3691439	0	0	0	0	0	0	0
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
	Time	**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	10.0859364	8.5941736	7.15930522	7.07688074	6.981732	7.1129369	7.30018175	7.5102965	7.78870242	7.69903475	7.61042481	7.52286	6.32166167	6.23615062	5.51071494	5.42720938
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	43.264166	39.083748	35.0627669	34.831786	34.565147	34.932827	35.45755	36.046362	36.8265483	36.5752695	36.3269548	36.08157	32.7154096	32.4757791	30.4428657	30.2088552
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	40.5220509	36.747206	33.11633	32.9077582	32.666988	32.998997	33.4728123	34.004499	34.708994	34.4820936	34.2578697	34.03629	30.9967071	30.7803249	28.9446395	28.7333321
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	37.4279075	34.110703	30.9200127	30.7367269	30.525146	30.816904	31.2332772	31.700505	32.3195914	32.1201991	31.9231588	31.72844	29.0573604	28.8672111	27.2540734	27.0683836
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	30.1557442	27.91413	25.7580094	25.6341533	25.491177	25.688333	25.9696991	26.28543	26.7037801	26.56904	26.4358892	26.30431	24.499315	24.3708209	23.2807369	23.1552564
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	25.5515848	23.99095	22.4898366	22.4036068	22.304065	22.441328	22.6372171	22.857033	23.1482919	23.0544844	22.9617835	22.87018	21.6135207	21.5240617	20.7651341	20.6777732
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.3159756	16.973431	16.6439501	16.6250234	16.603175	16.633303	16.6762988	16.724546	16.788475	16.7678851	16.7475381	16.72743	16.4516068	16.4319714	16.2653938	16.2462189
Solar fraction		1																							

Figure 20- Fully discharged tank on a partially sunny winter day with no immersion heater

From Figure 20, it can be realised that the demand cannot be meet if there is no additional heat and the top temperature of the tank is seen to be decreased to 30°C by the end of the day. It can be observed that there is a small amount of solar radiation that could be exploited.

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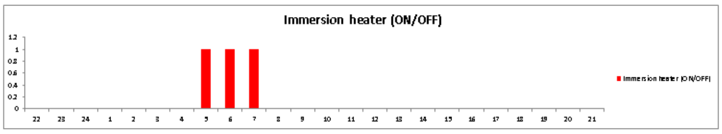


																						6			
	Time	22	23	24	1															16	17	18	19	20	21
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
	Time	**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0		0	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	2.4	2.4	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	12.585541	14.8859364	15.794174	14.3593052	14.2768807	14.181732	14.087706	13.9947885	13.902967	13.8122293	13.7225616	13.6339517	13.54639	12.3451885	12.2596775	11.5342418	11.4507363
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	50.268893	56.7153708	59.260555	55.2395742	55.0085932	54.741955	54.478461	54.2180764	53.960763	53.7064845	53.4552057	53.2068911	52.96151	49.5953458	49.3557153	47.322802	47.0887915
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	46.847198	52.6682552	54.966512	51.3356365	51.1270647	50.886295	50.648365	50.4132417	50.180892	49.9512832	49.7243828	49.5001589	49.27858	46.2389963	46.0226141	44.1869287	43.9756213
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	42.986231	48.1015775	50.121207	46.9305176	46.7472318	46.535651	46.326567	46.1199485	45.915768	45.7139951	45.5146028	45.3175625	45.12285	42.4517641	42.2616148	40.6484771	40.4627873
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	33.911802	37.3685174	38.73329	36.5771692	36.4533132	36.310337	36.169047	36.0294241	35.891448	35.7550995	35.6203594	35.4872087	35.35563	33.5506345	33.4221404	32.3320564	32.2065758
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	28.166591	30.5731915	31.52336	30.0222468	29.9360169	29.836475	29.738108	29.640901	29.544841	29.4499134	29.356106	29.2634051	29.1718	27.9151422	27.8256833	27.0667556	26.9793948
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.889945	18.418172	18.626725	18.2972447	18.278318	18.25647	18.234879	18.2135428	18.192458	18.1716228	18.1510329	18.1306859	18.11058	17.8347547	17.8151192	17.6485416	17.6293667
Solar fraction		0																							

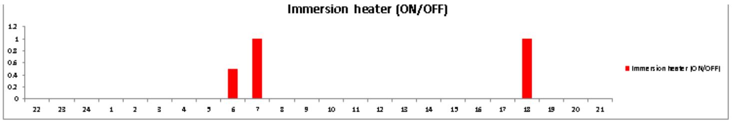
Figure 21- Fully discharged tank on a partially sunny winter day with immersion heater during off peak tariffs

First the usual off-peak immersion heater settings were implemented in order to supply the energy needed for the demand, and the result below were found:

If those settings are chosen, it can be seen that the total amount of the solar input is lost. However it was observed that improved settings could allow this energy to actually be supplied to the system. These new times for the immersion heater are shown below.

Calculations

Back to intro



	Time	22	23	24	1															16	17	18	19	20	21
Energy lost from **storage** [kWh]		0.109348	0.10805772	0.10678306	0.10552344	0.10427868	0.1030486	0.08813651	0.1007934	0.09960441	0.0984295	0.09726839	0.08242448	0.0951487	0.0940263	0.0929172	0.0918211	0.09073802	0.08966767	0.08860994	0.087565	0.08653178	0.08551105	0.08450235	0.08350556
Energy supply from **solar** Qsol [kWh]		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3019359	0.3691439	0	0	0	0	0	0	0
Energy **demand** for hot water Qd [kWh]		0	0	0	0	0	0	0	0	0	1.3933333	1.3376	0	0	0	0	0	0	0	0	0	1.11466667	0	0.64093333	0
	Time	**22**	**23**	**24**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Immersion setting (ON = 1/ OFF = 0)		0	0	0	0	0	0	0	0	0.5	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Energy supply from Immersion		0	0	0	0	0	0	0	0	1.2	2.4	0	0	0	0	0	0	0	0	0	0	2.4	0	0	0
Energy available in the tank	11.01	10.90216	10.7941045	10.6873214	10.581798	10.4775193	10.374471	10.2863342	10.185541	11.2859364	12.194174	10.7593052	10.6768807	10.581732	10.487706	10.3947885	10.604903	10.8833091	10.7936415	10.7050315	10.61747	11.8162684	11.7307573	11.0053217	10.9218161
T1	45.86	45.5515	45.2486897	44.9494479	44.6537359	44.3615122	44.072736	43.8257476	43.543291	46.6269672	49.172151	45.1511705	44.9201896	44.653551	44.390058	44.1296727	44.718485	45.498671	45.2473922	44.9990775	44.75369	48.1131347	47.8735042	45.8405908	45.6065803
T2	42.86	42.58748	42.3140414	42.0438312	41.7768084	41.5129355	41.252175	41.0291493	40.774096	43.558602	45.856859	42.2259832	42.0174114	41.776641	41.538712	41.3035884	41.835275	42.5397701	42.3128697	42.0886459	41.86707	44.9005854	44.6842032	42.8485178	42.6372104
T3	39.49	39.24293	39.0026476	38.7651961	38.5305456	38.2986631	38.069516	37.8735283	37.649396	40.096325	42.115955	38.9252651	38.7419793	38.530399	38.321314	38.1146961	38.581924	39.2010103	39.001618	38.8045777	38.60986	41.2756143	41.085465	39.4723272	39.2866375
T4	31.55	31.38225	31.2198808	31.0594221	30.9008561	30.7441606	30.589313	30.4568742	30.305416	31.9589375	33.32371	31.1675893	31.0437333	30.900757	30.759467	30.6198442	30.935575	31.3539252	31.2191851	31.0860343	30.95445	32.7558467	32.6273526	31.5372686	31.4117881
T5	26.52	26.40549	26.2924476	26.1807346	26.0703393	25.9612463	25.85344	25.7612345	25.655788	26.8069864	27.757155	26.2560417	26.1698118	26.07027	25.971903	25.8746959	26.094511	26.3857706	26.2919632	26.1992623	26.10765	27.3618028	27.2723439	26.5134162	26.4260554
T6	17.53	17.5034	17.4785881	17.4540682	17.4298374	17.4058925	17.38223	17.3619918	17.338847	17.5915247	17.800078	17.4705974	17.4516707	17.429822	17.408232	17.3868955	17.435143	17.4990717	17.4784818	17.4581348	17.43803	17.7133018	17.6936664	17.5270887	17.5079138
Solar fraction		0.100595																							

Figure 22- Fully discharged tank on a partially sunny winter day with improved immersion heater settings

In the settings exposed in Figure 22, the solar energies could be supplied to the system. However the immersion heating would need to be turned on at 6pm in order to deliver the energy required for the evening demand. That would involve cost consequences as it is not an off peak period, but it was seen that with the improved setting, the immersion heater need to be on for less time than in the previous situation presented in Figure 21. Actually it was on for 3h before and is now on for 2h30 so less electricity is consumed. Unfortunately, the cost for these improved settings is still higher but by only 7 pence.

Simulations were then run for each month during a full year, with the tank fully discharged, for a sunny day and for a partially cloudy day (50% cloud forecast). It was thought that this would give an idea of the worst case scenario for the system. The solar fraction was tried to be increased and even if that could be done with putting the immersion heater on in on peak period. However, if the solar fraction could not be increased, the off peak period were preferred.

The table below presents the immersion heater settings that would improve the solar fraction:

Table 6- Results for an all year simulation, tank fully discharged

	Tank initial state	Final Temperature	Immersion heater time	Solar fraction	Solar energy input
Jan	Sunny	45.3°C	1h45 off-peak	36%	2.4kWh
	Partially sunny	45.6°C	1h30 off peak 1h on peak	10%	0.67kWh
Feb	Sunny	52.4°C	1h30 off-peak	60%	5.4kWh
	Partially sunny	45.1°C	1h30 off peak 15min on peak	35%	2.3kWh
Mar	Sunny	57.8°C	1h30 off-peak	67%	7.4kWh
	Partially sunny	46.0°C	1h30 off peak	47%	3.2 kWh
Apr	Sunny	61.6°C	1h15 off-peak	76%	9.4kWh
	Partially sunny	48.8°C	1h30 off peak	54%	4.2kWh
May	Sunny	63.4°C	1h off-peak	82%	10.6kWh
	Partially sunny	47.8°C	1h30 off peak	52%	3.8 kWh
Jun	Sunny	65.8°C	1h off-peak	83%	11.5kWh
	Partially sunny	49.0°C	1h30 off peak	54%	4.3 kWh
Aug	Sunny	61.0°C	1h off-peak	80%	9.76kWh
	Partially sunny	48.8°C	1h30 off peak	54%	4.2kWh
Sept	Sunny	59.6°C	1h15 off-peak	74%	8.7kWh
	Partially sunny	47.9°C	1h30 off peak	52%	3.9kWh
Oct	Sunny	54.8°C	1h30 off-peak	64%	6.3kWh
	Partially sunny	46.7°C	1h45 off peak	41%	2.9kWh
Nov	Sunny	48.6°C	1h45 off-peak	46%	3.5kWh
	Partially sunny	46.1°C	1h45 off peak 30 min on peak	21%	1.4kWh
Dec	Sunny	46.4°C	2h off-peak	31%	2.2kWh
	Partially sunny	45.4°C	2h45 off peak	0%	0 kWh

In Table 6, it can be seen that, the maximum solar fraction is achieve for the month of June with 82% for a sunny day and 54% for a partially sunny day, and the minimum one is found for the month of December, with 31% for a sunny day and 0% for a partially sunny day. It is found that the solar fraction a above 35% from February to October in both weather conditions and only December and January have very low solar inputs.

4.3. **Conclusions**

It was seen during a summer simulation that the immersion heater part can be reduced as a large amount of solar energy can be available. If the tank is fully charged, there is no need to turn the immersion heater on. Actually as the storage tank has a high capacity of 500 litres, the energy present in the tank when it is charged is enough to cope with the demand. That means that if any solar input is high enough to be supplied, the solar fraction will be 100%. However, because the tank is fully charged, the temperatures inside it are quite high and the solar temperatures might not be high enough to provide more energy to the tank. In the case it can provide this energy, it was seen that care should be made regarding possible high temperatures (above 80°C) that could damage the tank.

If the tank is partially charged, there would be a need to turn the immersion heater for 2 hours if there are no solar gains. However, this time is reduced to 45 minutes if the forecast is set to 50% clouds allowing for a 70% solar fraction for the system. If the following day is fully sunny, the auxiliary heater need to be on for only 15 minutes and the system reaches 95 %.

In the case of the tank fully discharged, 7.2 kWh need to be add to the system if there is no solar input (3 hours with a 2.4kW immersion heater). This time can be adjusted to 1h30 if there is a forecast of 50% clouds and to 1 hour if the next day has 0% clouds. The solar fraction achieve in both cases are 54% and 82% respectively.

The simulation for one day of every month of the year was undertaken and it was observed that in winter, especially January and December, the solar energy inputs can be very low. If the immersion heater was put in the morning for too long, providing a too high energy input, these solar gains could not be exploited at all. It was seen that in some situation it would be beneficial to turn the immersion heater on in the evening so the tank has been filled with solar energy and needs less heat gains to supply the evening demand. Through the all year, high solar fraction could be achieve even if the tank is fully discharged when the simulation start, at 9pm.

It was understood that the control of SDHW system can be variable depending on the situation encountered and on the period of the year. The predictive algorithm can provide useful information on which situation will be faced and the control settings can be adapted and improved in order to maximise the solar fraction and minimise the use of the back-up system. This could help the user to fully exploit his solar system and to reduce his cost and carbon consumptions. The next section will discuss how this predictive algorithm could be improved and adapted in a practical way.

5. Practical implementation

Once the algorithm was fully understood and results were found, researches were made on ways to improved it and to implement it in a real control scheme for solar systems. First, following the ORIGIN project approach, it was understood that real data based models would largely increase the accuracy of the algorithm and complement the profiles created. A hardware implementation was then discussed, following by potential user interface possibilities. Those three topics are presented below.

5.1. Multiple regression analysis models

Regression analysis is a technique used to analysed multifactordata and investigate eventual relationships between variables (Montgomery, 2011). It can provide simple equations that will summarize or describe a set of data and will allow for future prediction of an unknown parameter. For example, if y is the unknown value also called the dependent variable and x_1, x_2…, x_i are independent variables that values are known, then a general multiple linear regression model will provide a prediction of y from the x_i and generate an equation having the following aspect:

$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_i x_i$, b_0 is the intercept

$b_1, b_2, \ldots, b_i$ are the regregression coeficient that can be interpert the same way as slope.

(Explorable.com, 2009)

This regression equation is etablished from a dataset where all the variables are known, including y. It will then be use to calculate y when x_1, x_2…, x_i are given. An essential aspect of this kind of analysis is then data collection and this method will not work at its best if the data it is based on are deficient. Moreover the choice of the independant variables is also critical as wrong choice will not provide good regression model.

In this project, it was thought that regression analysis could be used to generate more accurate profiles. That also was the strategy used within the ORIGIN project. Few multiple regression analysis equations were developed by this EU project, based on a 5-weeks monitoring work. The equations were generate using Excel, that has a functionality to develop these kind of models.

Within the ORIGIN project, the following data regarding the hot water system from the Centini house in Findhorn were acquired:

- The 6 nodes temperatures of the tank
- The DHW flow
- The DHW return temperature
- The DHW temperature difference
- The DHW energy
- The solar energy
- The solar flow
- The solar return temperature
- The solar temperature difference

Because the storage tank used for this project is not an indirect tank, the regression equations found in the ORIGIN project will not be valid for the case studied. Some other data were available for a more similar system than the one chosen in this project but there was no time to generate the regression models. However, the ORIGIN team produced a model that was calculating with accuracy the solar input, knowing the solar radiation and the tank bottom temperature. Although the number cannot be used here, it was interesting to see which values are related to each other. It was seen that the flow temperature needed to be calculated using the solar radiation and the tank bottom temperature. From the difference between the flow temperature and the tank bottom temperature, the solar input could be estimate. This method could give more accurate result than the one used here, based on SAP.

It was also thought that this regression method could also be used for calculating the real relations between the tank temperatures for different system situations. Improved storage losses and demand profiles could be generated. At this point, other weather forecast would maybe need to be used, like the outside temperature which is already available on the Excel program.

If a careful data collection is undertaken, the regression analysis method can provide accurate equation regarding system behaviour. It was seen that it could be a great opportunity to model in a more precise way the SDHW system. In a next part, discussion will be hold regarding the hardware implementation of the prediction and control algorithm created.

5.2. Hardware implementation

In order to implement the algorithm created in Excel in a practical way, it was understood that there will be a need for a hardware that could integrate the logic, that would be able to receive measurement from sensors and that is capable to take data from the Internet. Another point that would be interesting to achieve is that the program integrated into the hardware would be able to learn the system and user behaviour to adapt itself to any known situation. Deeper researches about microcontrollers were undertaken and the Arduino board looked like a possible solution for the wished application. Arduino is an open-source physical computing platform based on a simple microcontroller board, and a development environment for writing software for the board (Arduino, 2014). The Arduino platform integrates its own programming language which is comparable to C++ with slight modifications.

The main advantages of this system are that it is inexpensive and has an open-source platform that can provide support and examples. The Arduino platform proposes different type of board that have various functionalities. For this project, one of the major focuses was to be able to connect to the Internet in order to import the weather data. It was seen that the Arduino Ethernet shield can be used to access any non-password protected site. The main limitation with this microcontroller was its lack of memory. There are three pools of memory in the microcontroller used the Arduino boards. The flash memory is where the Arduino program is stored. There is also the SRAM (static random access memory) which is where the program creates and manipulates variables when the microprocessor runs and the EEPROM which is a memory space that the programmers can use to store long-term information (Arduino, 2014). The more powerful board found has a flash memory of 256k bytes, a SRAM of 8k bytes and a EEPROM of 4k bytes (Arduino, 2014). The problem is that if the Arduino run out of SRAM, the program might fail. As it was not known how much space the Excel algorithm would take when converted to the Arduino language, solutions where investigated about possible ways of communication with an external environment to support the hardware. A freely available generic proxy program, Gobetwino, was found to be a potential solution as it permits Arduino to communicate with a PC. Gobetwino can be downloaded from the internet and defines a set of command types that can be used as templates to create actual commands. Arduino can ask Gobetwino to execute these commands, and return something to Arduino (Arduino, 2014). The particular functionality that was very interesting for this project was the fact that with GoBetwino, the Arduino is able to send data to Excel or to create a CSV file to store them in a computer.

The Arduino structure would then be able to monitor the solar system while controlling it. Actually Arduino, with Gobetwino, will be able to receive the data from different sensors and send it to an Excel spreadsheet or a CSV file. In order to fulfil this monitoring work, the sensors needed would be:

- Temperatures sensors: Six of them for the hot water storage tank, one for the cold water inlet, and two for solar input and output temperatures.
- A pump monitoring sensor that would observe when the solar pump turn on, and at which power. That would allow for the calculation of the solar energy input by using the formula $Q=mcp\Delta T_{solar}$ where the ΔT_{solar} can be extracted from the solar system temperatures.

In order to accomplish a practical implementation of prediction and control algorithm created in Excel with the Arduino, the following step would need to be undertake. First, the algorithm would have to be translated into the Arduino language. This device would need to take decision on which control settings are the most adequate to the situation it faced. It will then communicated its decision to the immersion heater and will turn it on when required. At the same time the Arduino will received data from the different sensors, that will provide information about the state of the system, and that will be send to an Excel spreadsheet for future analysis.

The Arduino can offer a cheap way to control SDHW system. However it has its limitations which are mainly related to its lack of memory. As it was not known if the all algorithm could be put into just one Arduino board another alternative found was to run the program using the possible PC communication. However that would require a computer to be on each time the algorithm needs to run. Therefore, the improved solution proposed is to run the Arduino using Java. In this way the program could be launch into a server or directly into the Internet. The

Arduino will collect the data from the different sensor and send it to the server, or to the Internet, using the functionality of the Ethernet shield. The Java program will run the algorithm with the data sent and decides of the most adequate control settings. This information will then be send back to the Arduino that will turn on the immersion heater at the agreed times. This would require writing the algorithm in the Java language but this possible Java-Arduino communication can offer a great opportunity to improve the algorithm. Actually Java is a powerful programming language that can integrate learning processes. A more complex control system, similar to the NEST learning thermostat, which can learn the system behaviour and adapt the settings, could then be developed.

This section provided a scoping study of a possible implementation of the prediction and control algorithm with the Arduino microprocessor. Different propositions were made and solutions were proposed to cope with the eventual hardware limitations. An overview of how the control would work and how it would be able to monitor the SDHW system was exposed.

5.3. **User interface**

The user interface can play a great role in the energy use by SDHW systems as the householders can take uninformed decisions that could be critical for achieving the water heating system best usage. A trial conducted by the Energy Saving Trust outlined that “better advice to users on how to control their solar water heating systems (in terms of volume of hot water use, timing of back-up heating and hot water use, and temperatures required) is essential”. Actually if the user is aware of the state of the SDHW system, he has the choice to adapt his behaviour to exploit it efficiently.

The control algorithm would also be largely improved if it is able to “communicate” with the user. For example, input from the user stating that he is going on holidays will allow the control system to completely turn off the immersion heater for the time the user is not utilising his system.

An example of important outputs that could be useful for the user to know was shown for the algorithm presented, in the section 3.2. showing the model outputs. Another model that transmits the information to the user using internet is shown below:

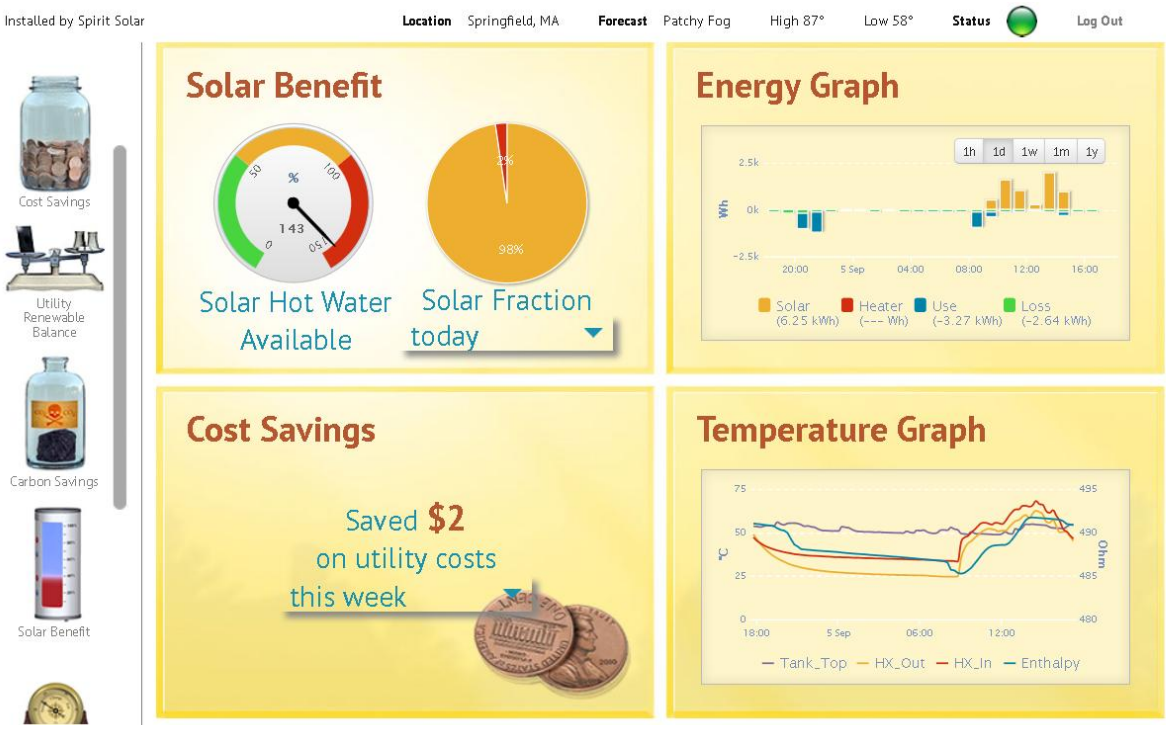


Figure23- Example of user interface

Source: (Amatis Controls, LLC, 2014)

In Figure 23, it can be seen that homeowners can check on the amount of thermal energy produced and use along with how much money they are saving. This example is given present conditions of the SDHW system, but it could integrate the predicted state calculated with the algorithm created.

It was seen that a user interface can improved the SDHW system performances. By transferring useful information like the solar gains, the cost savings and the system state, the user can adapt its behaviour and use his system in a aware way. Moreover an improved user interface will allow the user to specify its habit and potential modification of his domestic hot water usage, so that the control system can adjust itself.

6. Conclusions

6.1. Discussions and future work

This part of the thesis will review the different step undertaken through this project and exposed the results found. Eventual limitations and future improvement will be discussed.

The first step of the thesis implicated a scoping, investigation and knowledge gathering work presented in the form of a literature review. The different configurations of SDHW system were exposed. It was found that a standard UK system will have a flat-plate solar collector, working with an antifreeze working fluid, bringing the solar energy to a storage tank. For this project tank stratification was assumed and more information on whether or not it can be achieve should be further investigated. The back-up system was set to be an electric heater immersion. Data from the Findhorn Community were used to put number on some unknown values. However the system studied is a bit different from the one found in the Centini houses of the Findhorn community, and considerations of other technical specification, more relevant to the model built would be interesting. In the literature review, it was seen that the control of the SDHW system can play a major role on the efficiency of such structure. The figure below recalls the importance of control settings for achieving high solar fraction.

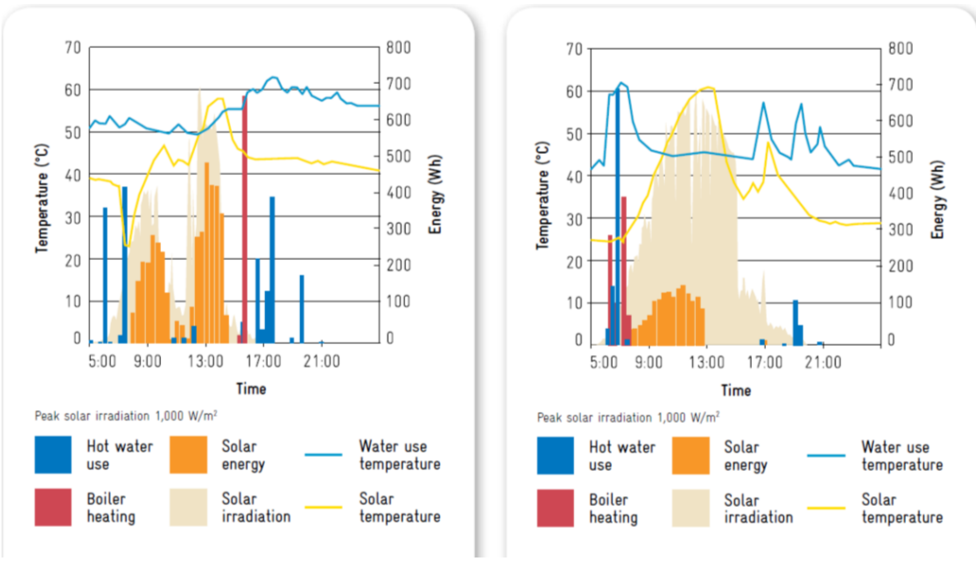


Figure 24-Importance of control in SDHW system

In Figure 24, it can be seen that wrong time setting of the back-up system will lead to a poor exploitation of the available solar irradiation. Therefore the settings of the auxiliary heater can play a critical role in the operation solar water heating system. It was suggested that a more informed decision could be made by implementing weather and demand forecast into the control of such system.

A model was built in Excel to give weather and demand predict ion that could support the control decision. The algorithm created incorporated a model of the standard UK solar system set up regarding the scoping process. The profile created in Excel seems to give reasonably accurate outputs but it has its limitations. The algorithm can access and use weather forecast from the Internet. However the methodology used to predict the solar radiation has not been tested and should be compared to real information and to some other prediction tool like the one proposed by GeoModel Solar. This later offer a solar radiation forecast to up to 48 hours, at reduced prices for academic research. The storage losses profile was based on previous work and was assumed to give reasonable output but could be improved by using a multiple regression analysis. The demand profile offered the possibility to set the demand and change it in case of modifications in the household habits. A more precise model, implementing more hot water device, could however be created. The solar calculations allow the transformation of the horizontal forecasted radiation into the solar input the hot water system. A deeper look could be taken to try to understand the problem faced with the solar altitude angle, explained in section 3.4. Moreover the calculations are based on a modified SAP equation and could be much more accurate if it use real data based regression analysis model. From data shown in the different profile the algorithm output the state of the system for the next 24 hours. In order to complete this calculation it was assumed that each node was carrying a percentage of the overall tank energy and that this percentage will remain constant over time. Though, the dynamic of the system is quite different from this and further study of the node temperature interaction with each other could give more accuracy to the model.

The prediction algorithm was then tested for different weather condition at different period of the year. The results showed that, in case of a sunny day, the solar fraction can reach fairly high value the all year round if solar energy can be harvested in an efficient way. There was a difference of back-up time and duration between winter and summer and also depending on weather predicted conditions. Actually in summer, the back-up heater part can be greatly reduced compared to winter month. Moreover in winter month, the solar fraction can be increased by supplying just enough energy to meet the morning demand but not too much so that the potential available radiation can be harvested. Additional heat from the back up might be needed to complement the solar input and be able to supply the evening demand. Therefore, if the next 24 hours predictions are known for the SDHW system and for the weather condition, those settings can rely on more up-to-date information and the timing of the immersion heater can be changed so that the maximum solar energy is harvested.

As it was seen that the weather and demand predictions could actually be beneficial to help with the control decision within a solar water heating system, the possible practical implementation of the algorithm created was investigated. It was seen that regression analysis techniques could give accurate equations, based on real data from the system where the system was wished to be implement. The Arduino board along with the Ethernet Shield was found to be a possible hardware implementation. The importance of an improved user interface was outlined and an examples of how it could look like was given.

6.2. **Overall conclusions**

This project investigates the possible implementation of weather forecast and demand prediction in a smart control scheme for solar domestic hot water systems. Through this thesis, the solar hot water systems and their available control options were reviewed in order to choose a standard UK structure to be tested. This system incorporates a solar collectors, a hot water storage tank and an electrical immersion back-up which specifications were taken from the Findhorn community case study.

A prediction and control algorithm was created in Excel to model the solar water heating system chosen. The algorithm uses inputs from weather, user demand pattern, system heat losses and system solar input. A methodology was undertaken in order to provide radiation forecast from cloud forecast freely available on the Internet. The program produced is capable to import these weather predictions and deducted the solar energy input to the SDHW system from them. The hot water demand is forecasted by the mean of timetables that need to be completed by the user. The advantage of this method is that, in case of changes in the hot water consumption, the user can specify it and the algorithm can adapt itself to the new demand profile. From this predicted energy inputs and outputs, the Excel program was able to calculate the state of the hot water system for the next 24 hours. It will highlight the available solar gains and the times at which the demand cannot be meet with the energy present in the tank. From this, it is then possible to set the times and durations at which the immersion heater will be on and see how they can be improved so that the solar gains are conserved while the demand is met.

The algorithm was tested for different weather conditions and for diverse periods of the year and it was found that the solar fraction could be increased by modifying the settings of the back-up system. The results showed that, in case of a sunny day, the solar fraction can reach high value the all year round if solar energy can be harvested in an efficient way. It was also observed that different weather and demand situations will require different control setting. Therefore the knowledge of weather and demand prediction could be beneficial in order to make a good control decision.

Due to the potential advantage of such improved controls, a last step of the project was undertaken to show the possible system practical integration and propose solutions on how the prediction algorithm created could be implemented into a practical control system. It was found that the Excel profile could be complement with a monitoring work. This later could give accurate information about the SDHW system and could offer the opportunity to produce regression analysis equations that provide a precise model of the system performances. The Arduino hardware was observed as an inexpensive potential solution to run the algorithm and deliver its outputs to the solar system. Finally, a thought about how the user could interface with the control system was presented. This part demonstrates the importance of an improved user interface that could integrate the user inputs of eventual changes in his hot water habits and allow him to see the actual and predicted performances of the system .

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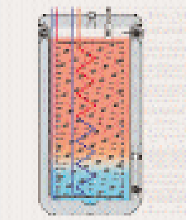
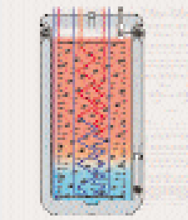
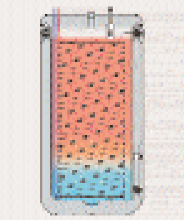
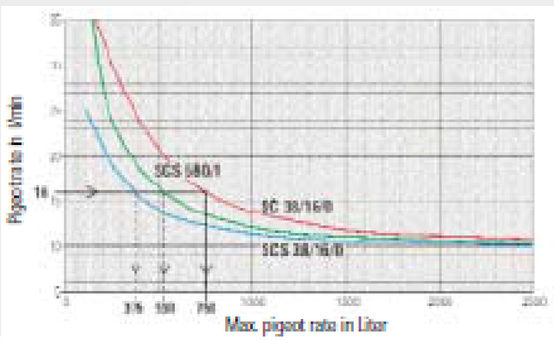
Appendix 1: Rotex Sanicube Specifications

Technical data Sanicube and Sanicube Solaris		Sanicube INOX SC 38/16/0	Sanicube INOX SC 38/16/16	Sanicube INOX SC 38/0/0
				
Basic data				
Total storage tank content	litre	500	500	500
Empty weight	kg	84	90	78
Total weight when filled	kg	584	590	578
Demensions (L x W x H)	cm	79 x 79 x 159	79 x 79 x 159	79 x 79 x 159
Max. permitted temperature of the storage water	°C	85	85	85
Standby heat expenditure	kWh/24h	1,4	1,4	1,4
Maximal operating pressure	bar	10	10	10
Material of the drinking water heat exchanger		Stainless steel	Stainless steel	Stainless steel
Domestic water heating				
Domestic water content	litre	24,5	24,5	24,5
Surface of domestic water heat exchanger	m²	5,5	5,5	5,5
Middle specific heat efficiency	W/K	2 470	2 470	2 470
Storage tank loading – heat exchanger (stainless steel)				
Water content heat exchanger	litre	10,4	10,4	–
Surface loading heat exchanger	m²	2,3	2,3	–
Middle specific heat efficiency	W/K	1 040	1 040	–
Storage tank loading – heat exchanger 2 (stainless steel)				
Water content heat exchanger	litre	–	10,4	–
Surface loading heat exchanger	m²	–	2,3	–
Middle specific heat efficiency	W/K	–	1 040	–
Solare Heizungsunterstützung (Edelstahl)				
Water content heat exchanger	litre	–	–	–
Surface loading heat exchanger	m²	–	–	–
Middle specific heat efficiency	W/K	–	–	–
Heat technical / Thermal efficiency data				
Efficiency key number N_L accord to DIN 4708 [2]		4,1	4,4	4,1
Continous output Q_D accord to DIN 4708	kW	35	50	35
Max. pigeot rate for the time of 10 min. with 35 KW with (T_{KW} = 10 °C/T_{WW} = 40 °C/T_{SP} = 60 °C)	l/min	30	31	30
Hot water quantity without retreating with 15 l/min pigeot rate (T_{KW} = 10 °C/T_{WW} = 40 °C/T_{SP} = 60 °C)	litre	412	412	412
Hot water quantity with reheating with an output of 20 KW and 15L/min pigeot rate (T_{KW} = 10 °C/T_{WW} = 40 °C/T_{SP} = 60 °C)	litre	837	843	837
Short term water quantity in 10 min.	litre	300	310	300
Pipe connections				
Cold- and hot water	inch	1" male	1" male	1" male
Heating flow- and return	inch	1" male	1" male	1" male
Ref.no.		16 50 16	16 50 17	16 50 15

1) Suitable for solar-operation with ROTEX Solaris
2) With retreating with 35 KW, 80 °C flow temp. 65 °C storage tank temp. 45 °C hot water tem. and 10 °C cold water temp.

Hot water efficiency in dependency to the pigeot rate

- storage tank temp. 60 °C
- spigeot temp. 40 °C
- Boiler output 20 KW
- Cold water temp. 10 °C



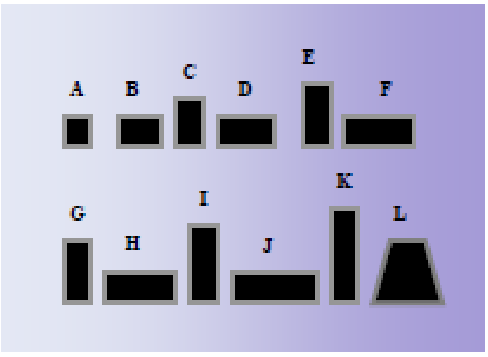
Appendix 2: Collector Specifications

TECHNICAL SPECIFICATIONS

Version 10.12

COLLECTOR TYPE: AES Serpentine and Headers & Risers operation

MODELS:



MEASUREMENTS AND WEIGHTS:

MODEL	HEIGHT mm	WIDTH mm	GROSS AREA m^2	APERTURE AREA m^2	WEIGHT kgs
A	1175	1032	1.2	1.05	14
B	1175	1500	1.7	1.58	18
C	1500	1175	1.7	1.58	18
D	1175	1945	2.2	2.05	23
E	1945	1175	2.2	2.05	23
F	1175	2130	2.5	2.26	25
G	2130	1175	2.5	2.26	25
H	1175	2880	3.3	3.08	30
I	2880	1175	3.3	3.08	30
J	1175	3770	4.4	4.24	41
K	3770	1175	4.4	4.24	41
L	Triangular collector - sizes and weights vary				

ABSORBER PLATE:	Aluminium fins metallurgically bonded to rhombic shaped copper water ways providing large water to wall contact for maximum heat transfer. Sputter coated selective surface: Solar Absorption = 96% ± 2, Thermal Emission = 7% ± 2
GLAZING:	High quality, twin-wall polycarbonate. Light weight, long term weather resistance and outstanding thermal insulation properties. Solar transmission = 85%.
BACKING:	Melinex film, ensuring the collectors are completely waterproof
COLLECTOR BOX:	Aluminium box section with all round fixing channels for easy fitting. A sensor pocket is fitted at the appropriate location
INSULATION:	Rigid PIR foam, manufactured with zero ODP
FLOW AND RETURN:	15mm copper
FLUID CONTENT:	0.6 litre per 1 square metre of collector area
RECOMMENDED FLOW RATE:	0.5 litre per square metre of collector area per minute
TRANSFER FLUID:	100% Tyfocor antifreeze mixture (recommended)
TEST PRESSURE:	15 Bar
MAXIMUM WORKING PRESSURE:	10 Bar
PRESSURE DROP:	10 kPa at flow rate of 0.03 litres per second, per 1 square metre of collector area
FIXING METHODS:	(1) Retrofit on top of roof cover (2) Flat roof mounted with A-frames and/or ballast or roof fixing – (See separate fact sheet or installation manual for fixing details)
ZERO LOSS EFFICIENCY:	0.633
HEAT LOSS COEEFICIENT:	2.907 W/m^2K
TESTED BY:	University College Cardiff, TNO The Netherlands, National University of Singapore, EN12975 by ITW
LIFE EXPECTANCY:	In excess of 25 years
APPLICATIONS:	Small to large domestic hot water systems, industrial process and swimming pool heating
GUARANTEE:	10 years

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