An Analysis of a Solar Thermal Heating system at Blacklake Farm

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Abstract
A first pass model of the solar thermal heating system with phase change material thermal stores at a Hampshire residence is explained and the addition of fireplace back boilers explored. The central heating circuitry is planned with a potential control system studied. Future work is set out based on improving the model with more accurate data collection.

Introduction
Within the UK, 47% of all final energy consumption is used for heating purposes. Figure 1 below highlights that of this heat 63% and 14% are used for space heating and hot water heating respectively, this significant proportion of demand is currently met by 80% direct fossil fuel combustion (88% gas, 9% fuel oil), 15% from an electricity grid running on 60% fossil fuel, with only the remaining 5% being met by more unconventional methods of biomass and other sources. (1) (2) With the UK aiming for 80% reduction in CO₂ emissions by 2050 and with this significant heating demand being to large to simply be placed onto the electricity grid, decentralised renewable and low carbon heating options will play an important role.

Solar thermal collectors have been shown to work effectively in the British climate, the energy saving trusts field trial of solar thermal systems for hot water heating found 60% of hot water could be provided by adequately installed and operated systems. (3) Integral to these systems like other intermittent renewable systems is energy storage. For hot water heating solar thermal systems, a hot water storage cylinder is used, a component which is already commonplace in homes. Hot water accounts for a larger proportion of energy demand for heating in new well insulated homes, however the UK housing stock is largely poorly insulated and old leaving space heating the largest primary energy demand in properties (63% of UK heat demand). For renewable and low carbon sources of fuel to effectively provide space heating, energy storage will play an important part.

Phase change materials (PCM’s) directly store thermal energy in the form of both sensible and latent heat, resulting in higher energy density than sensible stores alone due to the large energy associated with a phase change, typically solid-liquid (4). Paraffin waxes are used in available PCM stores due to their large phase change enthalpy 200-250kJ/kg and low melting points 50-70°C (4). Heat energy collected from solar thermal panels is used to heat up and melt the storage material upon charge, and then upon discharge the heating circuit can access heat energy from the store on demand. (4)

A solar thermal collector system installed at Blacklake Farm in Hampshire with 80kWh of Phase Change Material thermal energy storage, has provided an opportunity to study such heating scenarios. An interim report set out the goals of achieving a first pass model of the heating system on the farm and highlight how future work can build towards a potential control system.
Experimental

The Blacklake Farm system hardware consisted of a solar thermal array of five panels, each with a collector area of 2.03 m$^2$ and standard efficiency of 41% (5). The storage was made up of eight 10kWh ‘Power Tank’ thermal stores with their phase change at 50/54°C, each stores maximum input/output power was 1.4kW (11.2kW total). The oil boiler a ‘Grant Vortex 15/26kW’ (91% efficiency) (6) provided backup to the heating system with potential to feed into the thermal store. Initially the systems had proposed two wood burning stoves with a back boiler capacity of 11.2kW which could feed into the thermal stores, these boilers were not installed but will be investigated as a potentially low carbon addition.

Energy Demand Profiles
An estimation of heat demand was calculated using the annual oil usage a Blacklake farm of 3600l of kerosene. With the minimum efficiency of the boiler 91% and the energy density of kerosene 10.27kWh/l the annual heating demand was calculated to be ≈34’000kWh. This was conventionally split for a typically dwelling such as Blacklake as 30% heat demand for hot water and 70% heat demand for space heating (7).

Yearly data of one-hour time steps was available for solar irradiance and dry bulb temperature, for Gatwick Airport which is along the same latitude as the site and just 60 miles away. This data was used to model the demand and energy inputs into the system.

The space heating simulation was based around the simplified model of constant heating and maintaining an indoor temperature of 18°C in the property. The outside temperature was then used to calculated the hourly energy input needed to maintain 18°C. The sum of all the degrees below 18°C over the entire year was taken, the annual space heating energy was divided by the sum of all the degrees below 18°C. This gave an estimate of heat input needed per kWh/°C below 18°C to maintain the house temperature at 18°C in each time step based on outside temperature.

![Figure 2](image.png)

*Figure 2. First two days of February 2012, blue bars indicate energy input in kWh needed to keep the indoor at 18°C based on the outside temperature shown by the red line.*

Hot water demand typically has little seasonal variation but a large daily fluctuation. A daily demand profile based on the yearly hot water heat demand estimate was generated reflecting the literature reported hot water peak demand, shown in Figure 3. (7)

![Figure 3](image.png)

*Figure 3, the hot water energy demand in kWh for a two day period.*
Figure 2 and Figure 3 are summed together over the entire year to give the total demand profile for each time step over 365 days. Figure 4 shows the heating energy demand (space heating + hot water heating) over a two-day period for July and February, related to the outside temperature.

![Figure 2 and Figure 3 summed together](image)

**Energy Generation Profiles**

The solar input energy was based upon the collector standard efficiency (41%) and the site irradiance data only, this has a typical seasonal and diurnal profile, shown in Figure 5.

![Figure 5, top yearly profile for solar energy collected by array, (bottom) first two days of February solar thermal energy collected by the system.](image)
For the addition of fireplaces into the system their use was directly linked to the outside temperature and time of day. The model simulated fireplace contribution into the heating system of 11.2kW if the outside temperature was below 8°C during daytime hours 8:00-21:00, shown in Figure 6.

![Figure 6](image)

*Figure 6. First two days in February hourly fireplace input in kWh shown by the blue bars when operating criteria met, red line showing outside temperature.*

The thermal stores where modelled as being charged when solar and fireplace contribution was greater than the heat demand in a given time step and discharged if solar and fireplace contribution was less than the heat demand in a time step. The round trip efficiency was taken as 100%. If the level of the store was less than the demand, then the oil boiler was called upon to input the shortfall in energy. Figure 8 shows the completed system showing fireplace and solar generation contribution, hourly heat demand, when stored energy is utilised to meet demand, and when the oil boiler is called upon to meet shortfalls in supply. Figure 8 also shows how the store level can be modelled as the solar and fireplaces feed into it.

![Figure 8](image)

*Figure 8. First two days in February modelled with the initial level of the stores set to 0, (top) showing when each form of energy input is contributing to meet the energy demand, (bottom) showing the level of the stores other the period.*
Results and Discussion
With a first pass model of the system, the performance could be studied. Figure 9 shows how energy was input into the heating system over the year 2012, while Table 1 gives the energy inputs. The solar generation contributed 5558kWh into the heating system, an equivalent saving of 541 litres of kerosene saved (15% reduction). The stores allowed the utilisation of 2448kWh of solar energy generated (44%) to be used in a later time step. The maximum capacity of stored energy reached over the entire year was 60kWh, 75% of the stores maximum capacity Figure 11. In this scenario the stores seem somewhat over sized as the maximum amount of store capacity was never achieved and only 16 days of the year did the amount of storage capacity needed exceed 30kWh Figure 11.

![Graphs showing energy input over the year](image)

**Figure 9**, the cumulative sum of energy input from (top) oil boiler, (middle) solar thermal panels, (bottom) stored solar energy.

<table>
<thead>
<tr>
<th>Fuel Source</th>
<th>Energy Input (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Boiler</td>
<td>29010</td>
</tr>
<tr>
<td>Solar Generation</td>
<td>5558</td>
</tr>
<tr>
<td>Energy Stored</td>
<td>2448</td>
</tr>
</tbody>
</table>

*Table 1*, annual energy input from each fuel source.

The system was also modelled with the addition of the wood burning stoves with back boilers as an extra renewable generating source which with the ability to feed into the stores can reduce the amount of energy input from oil. The wood burners where modelled according to the operating criteria stated in the experimental. If the fireplaces are operated according to the models criteria 16'352kWh can be generated over the year, with the 5'558kWh of solar generation the total saving of oil is 2’133 litres (59% reduction). The operating criteria for the fireplaces means they generate typically on days when solar generation is low, this negative correlation seen from the gradients in Figure 10 is convenient as it allows the maximum amount of renewable energy to be utilised throughout the year. The value of 16’352kWh of fireplace generation amounts to 3.70tonnes of wood per annum.
Table 2, annual energy input from each fuel source.

<table>
<thead>
<tr>
<th>Fuel Source</th>
<th>Energy Input (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Boiler</td>
<td>14’346</td>
</tr>
<tr>
<td>Solar Generation</td>
<td>5’558</td>
</tr>
<tr>
<td>Fireplace Generation</td>
<td>16’352</td>
</tr>
<tr>
<td>Energy Stored</td>
<td>8’883</td>
</tr>
</tbody>
</table>

With the fireplace and solar system the capacity of the thermal stores is much more utilised when compared with the solar only system, as shown in Figure 11. The store is frequently filled to its 80kWh capacity over the colder periods of the year when the fireplace is heating, this being said the capacity of the store is well sized in this scenario as the frequency of the full charge events is not so frequent that large quantities of energy is curtailed. The stores are integral to the system as without their presence 8’883kWh of energy would have been wasted/curtailed from the fireplaces and solar. Fireplaces could be turned off if this level of storage was unavailable but solar systems would have to be curtailed.

Figure 10, the cumulative sum of each energy input over the year 2012, in descending order: Oil, Solar, Fireplaces, Energy Stored.
Control system

The control system of the Blacklake installation has proven to be inadequate, therefore it was set out as a goal to establish control system design which could be used as a template for designing a new control system for Blacklake. Appendix 1 lays out the circuit diagram of the system with the important thermal sensors and pumps necessary for control. The two loads are split into hot water and space heating, with the solar thermal panels and boiler as inputs. Appendix 1 lays out the control logic for charging the stores with the solar panels and the boiler based upon the sensor reading of ‘temperature within the store’ as an indicator of store level. It also gives switching logic to the pumps to meet current demand based upon the level of the store, i.e. call upon combined contributions of boiler and store if load is high.

A feature which is desirable to add to future work on modelling the system is reducing the boiler cycling to improve efficiency and boiler lifespan. Such a system would require accurate data on the forecasted generation and demand on the heating circuit, such that the boiler could top up the stores to match forecasted demand when it is called upon, thus reducing the need for it to be called upon in following time steps. The logic for this system is shown in Appendix 1: If demand is higher than the maximum power of the store or higher than the current capacity of the stores, the boiler is called to meet heating demand bypassing the stores but additionally, based upon forecasted generation/demand in future time steps, simultaneously feeds energy into the store.

It could be possible to forecast the future energy balances in the system based upon either historical data or better real time weather data streamed form a reliable source. Since outside temperature and solar irradiance are currently the only two inputs into the heating model this could be augmented relatively simply.
Improvements / Future Work

The time resolution of the data used within the model (1 hour period) would ideally be reduced to 1 minute. The reason for this is that hot water demand usually is not called upon for hours at a time, typically the time scales of minutes. Therefore, the true peaks in demand may not be shown in this model as the hot water use has been spread over one hour to give an average (lower) value. It is true a water cylinder is employed in the Blacklake system which smooth’s out hot water peak demands but to what extent has not been explored.

The space heating model of maintaining a constant indoor temperature is useful for a first pass and should be relatively accurate if this method of heating is employed. However, the exact heating control settings for Blacklake are not known, in which case space heating demand would have to be adjusted.

To build upon the model of this system and give a more accurate energy balance of the Blacklake Farm heating system it would be most desirable to collect data from the property itself. This way the exact space heating and hot water heating data needed could be collected over a smaller time resolution. The hot water demand could be measured from the switching frequency of the pump on the outflow of the hot water cylinder and a temperature sensor in the water cylinder providing data on the temperature of water provided. The space heating data similarly could be collected from a sensor on the radiator circuit pump and the temperature of water into the inflow and outflow of the radiator circuit. The system is currently running solely on the oil boiler, so a sensor measuring the total energy output of the boiler, based on the outflow temperature of the boiler feed in pipe, could validate the space heating and water data collected and also provide the efficiency of central heating system. Data collected in this way would give a more accurate model of the heating system at Blacklake.

If the above data is collected it could provide important detail into the efficiency of the central heating system, further work however is needed to incorporate a better model of efficiency for the thermal stores and the solar thermal panels. The stores are not ideal (<100% round trip efficiency), temperature readings of the thermal energy lost from the store over a given time period would provide their efficiency which could be incorporated into the model. The solar panel efficiency is well documented (5) and is related to a number of factors, importantly; the outside temperature solar irradiance and outlet and inlet temperature of the working fluid. A better model of the store with temperature modelled would be needed to accurately model the thermal panel efficiency based upon outlet and inlet temperature.

The fireplaces have been shown to be a valuable addition to the heating system. If they are added then they will not only contribute heat into the thermal tanks/central heating system, but they will reduce the space heating demand due to their direct heat output, this would need to be explored. If oil was to be removed completely from the heating system an electric heat pump could also be investigated.

As the system stands currently the solar panels and thermal stores stand idle with the oil boiler contribution 100% of the central heating system energy. It has been discussed how the thermal stores are currently over sized for the solar generation alone, only reach 60% of their maximum capacity once per year. Currently as the solar generation feeds straight into the stores, then indirectly heats the central heating of the home the system is unable to apply for a feed-in tariff. Solar thermal feed-in tariff is only available for solar thermal systems providing thermal energy for water heating only at 19.74p/kWh, the highest within the renewable heat incentive (8). With a change of heating circuitry and the installation of water cylinders with the capability for solar thermal connection, the system could be rearranged such that solar energy only covers hot water needs. This arrangement would make the phase changer stores redundant but could increase revenue of the solar thermal system through the feed-in tariff.
Conclusion

The first past model built and explained for these works is useful for understanding the energy balances of the heating system at Blacklake. A much more detailed model of heating demand based upon accurate data from Blacklake as well as accounting for efficiency within; the central heating system, solar panels and thermal stores, would need to be included. If data can be obtained from the Blacklake residence to generate a more accurate demand profile, then forecasting demand in future time steps would be possible. With the ability to forecast future demand accurately and also draw upon future generation capacity it would be possible to include the feature of reducing boiler cycling by contribution into the stores.

With the addition of these features into the model, it could then be incorporated into a control system based around monitoring temperature and controlling pumps around the central heating system, as explained in this report Appendix 1.

The addition of fireplaces should be considered and allowed for if this project is taken further forward as they have been shown to greatly decrease the central heating systems reliance on oil. The thermal stores are well sized for allowing fireplace space heating to be incorporated into the system. Whether in the short term or permanently if the solar thermal contribution could be isolated to water heating alone then the feed-in tariff could increase revenue from the system.

Blacklake farm offers a good opportunity to showcase how thermal energy storage can be utilised to reduce the heating dependence of domestic dwellings of fossil fuel. These works have highlighted the potential at Blacklake and explained what immediate further works would be beneficial to work towards an accurate system model and control system to hopefully bring this heating system back online.
References

Appendix 1. Circuit diagram of system and layout of control system logic.

**Solar Thermal Input**
- If $2S_t > 1S_t$
  - Pump 1 = On
  - Store = Charging

**Supply of Space Heat**
- If Radiator Circuit = On
  - then Space heating demand >0
    - if charge in the store ($1S_t$) >0
      - Pump 3 = On
      - Pump 2 = On
        - if Space heating demand > 11.2kW
          - Pump 3 = Off
          - Pump 2 = On
        - elseif forecasted Gen(t) < forecasted Demand(t)
          - Pump 5 = On($t_{top-up}$)
      - elseif charge in the store ($1S_t$) = 0
      - Boiler = On
      - Pump 2 = On
          - if forecasted Generation(t) < forecasted Demand(t)
            - Pump 5 = On($t_{top-up}$)

**Supply of Hot Water**
- If $3S_t <$ set point $T$
  - then cylinder input needed >0
    - if charge in the store ($1S_t$) >0
      - Pump 3 = On
      - Pump 4 = On
        - if Space heating demand > 11.2kW
          - Pump 3 = Off
          - Boiler = On
          - Pump 4 = On
        - elseif forecasted Gen(t) < forecasted Demand(t)
          - Pump 5 = On($t_{top-up}$)
      - elseif charge in the store ($1S_t$) = 0
      - Boiler = On
      - Pump 2 = On
          - if forecasted Generation(t) < forecasted Demand(t)
            - Pump 5 = On($t_{top-up}$)

**Legend**
- $1S_t$ Thermal Sensor
- Pump
- Blending Valve
Appendix 2, block diagram of control logic allowing boiler to meet demand and feed into store based upon forecasted energy balances.