DEVELOPMENT OF A DETAILED SIMULATION MODEL TO SUPPORT EVALUATION OF WATER LOAD SHIFTING ACROSS A RANGE OF USE PATTERNS

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ABSTRACT

As electrical power networks become increasingly dominated by intermittent renewable generation both at the grid level and decentralised, their operation presents new challenges. One mechanism that has been proposed as a potential solution is demand shifting of loads. This potential for load shifting is difficult to assess given variations and uncertainties in user behaviour and weather particularly for modern hybrid systems, which often include weather dependent solar and heat pump systems and complex controls.

This paper provides details of an integrated building simulation modelling approach intended to support load shifting studies, with a specific focus on the load shifting potential of hybrid domestic hot water storage systems. The example domestic hot water system investigated here comprises an air source heat pump coupled with solar thermal collectors and a storage tank featuring supplementary immersion heating for control of Legionella and top up heating. The hybrid hot water system and its controls are explicitly modelled at a level of detail sufficient to closely replicate the actual system behaviour.

User behaviour in this case affecting the quantity and timing of hot water draws has the potential to strongly influence water heating requirements, the solar hot water system effectiveness, and the potential for load shifting. The development of a set of stochastic water draw profiles to represent an appropriate range of behaviours for the UK context is described.

These different domestic hot water use patterns are then made available to facilitate the evaluation, in a detailed building and hybrid energy system model, of load shifting potential and effectiveness across a representative range of weather and behaviour.

While the case study presented here is for a specific situation, it is proposed that the methodology is more generally applicable.

INTRODUCTION

Concerns regarding volatility of fossil fuel prices, security of supply and climate change have increased for the use of renewable energy sources in the built environment. Considerable renewable penetration is expected over the next few decades with projections in Europe set to exceed 20% gross electrical generation by the year 2020 (EEA 2014). Exploitation of solar energy, wind and other renewables is a formidable challenge because of unpredictability of supply and mismatch in timing of energy demands and supplies. For example, solar energy is usually available when there is no need for heating and high winds at night will not contribute to offsetting daytime peak electrical demand. The need therefore is to provide a mechanism to match supply and demand. Whereas not much can be done to shift renewable supplies it is possible to shift demand and reasonably maintain operating performance acceptable to the user.

THE ORIGIN SYSTEM

We report initial results from the EU FP7 project ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) (URL 1). Within the project, a system to facilitate demand shifting of thermal and electrical loads is to be commissioned to enhance overall energy performance in terms of reducing dependence on conventional energy resources and increasing dependence on renewable resources. The sites for energy management are three eco-villages in Scotland, Italy and Portugal. Representative domestic buildings are being monitored extensively to inform about energy use patterns and potential demand shifting potential. Climatic boundary conditions are also monitored using local weather stations. The ORIGIN system overview is shown in figure 1.

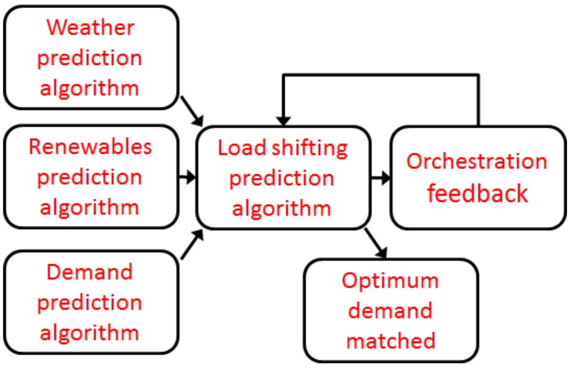

Figure 1 ORIGIN algorithm

The algorithm for the ORIGIN system relies on automatic acquisition of local weather data from which a weather prediction algorithm will generate weather for the near future (24 hours). This includes dry bulb temperature, direct and diffuse solar radiation and wind speed. Near future weather and demand predictions allow an assessment of supply / demand matching to be made, the available opportunities for load shifting are quantified (and adjusted based on feedbacks) and a decision made on how best to orchestrate these opportunities to close the gap.

The simulation modelling described here is to underpin various elements of the ORIGIN project:

- The first is to give insights and assist in the quantification of orchestration opportunities,
- The second is to assist in the evaluation and quantification of effectiveness of proposed orchestration algorithms,
- The third is to support investigations into improvements in existing systems or design of new systems which better support load shifting in future.

AIM

This paper reports on the development of detailed dynamic simulation modelling at sufficient detail to provide a test bed for load shifting analysis. The specific case presented is of hot water heating in a solar / heat pump / storage hybrid system. The importance of variations and uncertainties in behaviours is identified and a set of representative water draw patterns proposed. The case study is used to demonstrate how patterns of water use are related to potentials for load shifting and have an impact on solar utilization and heat pump energy input. Several examples of model outputs are used to illustrate the operation of the detailed model and the type of system performance insights made available for use in load shifting analysis.

SITE DETAIL AND MONITORING

Domestic buildings built to modern standards lend themselves well to the ORIGIN scheme because they are well insulated and have lower air leakage rates than older buildings. These factors make load orchestration more feasible. Heating and cooling are not necessarily the predominant energy loads in such buildings, rather the provision of hot water and electricity can form the major proportion of demand and these offer prime opportunities for orchestration.

The simulation model chosen as case study represents a building and hybrid thermal energy system of a type common in the ORIGIN communities and of a type becoming more common in general because of increasing building performance requirements across Europe. The model is built utilising fabric and systems specifications taken from design documents and was initially calibrated by comparing against available monitored data from which control settings and occupancy profiles have been tuned. This monitored data is obviously limited to the specifics of climate and occupant behaviour during the monitoring period. Therefore, further comparisons have been made against similar data gathered in other monitoring exercises to confirm that simulation results provide reasonable results out with the winter monitored period.

Figure 2 shows Findhorn; the Scottish eco-village where monitoring studies are being carried out. Figure 3 shows the example apartment building that is the focus in the work presented here. The apartment block is built to modern Scottish Building Regulations (SBS 2012). Extensive monitoring has been deployed across the ORIGIN communities including system and environmental measurements.

Figure 2 Findhorn eco-village (monitoring

Figure 3 Apartment block (monitoring site)

BUILDING AND SYSTEM MODELLING

A top floor apartment was selected from the building of figure 3 for detailed thermal modelling. The apartment was zoned into living area, sleeping area, sunspace and roof space. Figure 4 shows a wireframe rendering of the thermal simulation model used for predicting performance. ESP-r (Hand 2011, ESRU 2001) was used as the modelling tool because of its integrated simulation capabilities across thermodynamic “domains” (i.e. constituent parts of a model) as described by Clarke and Tang (2004). In order to fully assess the thermal performance of the building and the interaction between its fabric, occupants control and systems, the following domains are included within this model: building fabric, HVAC plant, solar insolation and shading, mass flow networks for both air flow and water flow in the hydronic circuit and electrical power flow network domains.

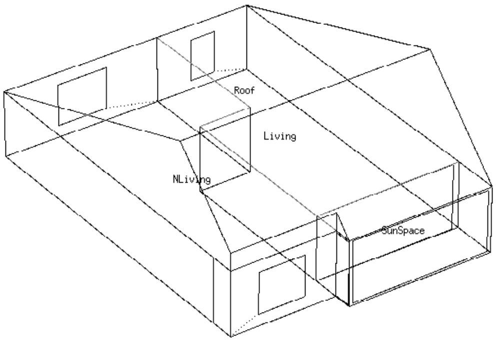

Figure 4 ESP-r dynamic thermal model

Within the model each of these domains is explicity defined. Well defined optimised solvers exist for these domains that solve for governing thermodynamic parameters at short intervals of time (time steps). The critical feature of integrated simulation is the time step level information exchange between these solvers due to which domains are solved based on fresh information becoming available each time step. For example the air flow solver gets inputs from thermal simulation regarding air temperature in each space and can dynamically accommodate density variations of the air in its solution. As a further example the electrical network knows about the state of the heat pump which is controlled from knowlede of space and buffer tank temperature which in turn are calculated during building and plant solution respectively. From this knowledge adjustments are made to the electrical network.

This form of the model described above allows interactions between the different energy subsystems in the building to be accounted for. For example, a sun space is present in the real building and this necessitates explicit shading and insolation analysis be carried out in conjunction with thermal simulation. This is coupled with an explicit model of the hydronic plant shown in figure 5. In the plant model, flows are predicted using a hydronic mass flow network in order to explicitly account for pressure and flow relationships. Finally, the building model includes an electrical network that allows the electrical demand (lighting, HVAC, appliances) and production (PV) to be explicitly tracked. Various air flows in an around the building are modelled by a zonal / network air flow model.

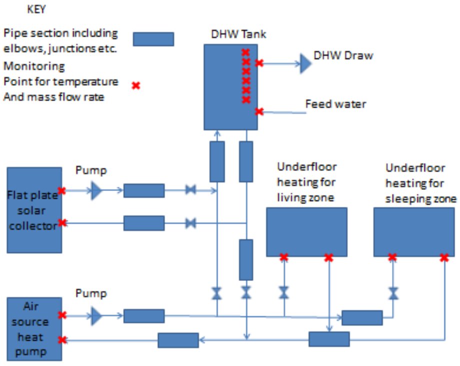

Figure 5 Explicit plant model schematic

The dwelling has highly insulated and airtight construction and mechanical ventilation with heat recovery. The conditioning system servicing the dwelling (figure 5) is a wet central heating system consisting of a low temperature air source heat pump that supplies both space and water heating. Space heating is by means of underfloor heaters within the whole of the dwelling except the sun space. The heat pump also supplies water to a hot water storage tank and can service both space and water heating simultaneously. A solar thermal system provides renewable heating to the water tank that can be heated either from the heat pump or from the solar collector. A boost immersion heater is also present in the hot water tank for topping up hot water and fulfilling hygiene obligations. It is important to note that hot water tank charging is done either by the heat pump or by the solar collector but not by both simultaneously. The boost immersion heater is independent of both.

Due to the various flow configurations in parallel branches and associated control interactions it was desirable to model flow by resolving it using network flow analysis (Lorenzetti 2002). Hence, a flow network modified for hydronic systems was developed and coupled with the plant network. The flow network simultaneously solves for flow rates as functions of pressure difference in each of the connections while maintaining mass balance. A pump curve modified from Grundfos (2005) was used to model water pump performance and a water stratification algorithm (Wang *et al* 2007) was used to predict the hot water storage tank performance. The solar collector performance prediction relied on an algorithm described by Thevenard *et al* (2004).

CONTROLS MODELLING

Recommended control for heating of the water tank is provided in the installation and operation manual (Daikin 2010). It includes set points for operation of solar collector, heat pump and immersion heater. Figure 6 shows the decision flow diagrams for solar heating and top up immersion heater. The figure is annotated by sensor information represented by S1 to S7, which are the sensors that are needed for recommended control. In brief, the solar collector was set to operate any time its temperature was more than 10°C above the inlet point in the tank. The heat pump was time controlled; with manufacturer recommended control imposed that allowed water heating between 0700-0900 in the morning and 1600-2300 in the evening. This timing was changed to study load shifting as described later. The immersion heater provided top up heating and was scheduled to be operated once a week for one hour ostensibly for legionella treatment.

The system control logic was decomposed to digital (ON/OFF) logic and implemented as such within the simulation environment as shown in table 2. Within the table the first 7 controllers are sensed conditions as described in Figure 9 (S1 to S7). The next 4 controllers (8 to 11) are the logical inverse (logical NOT) of controllers 1 to 4, these ease in further control logic implementation. Controllers 12 to 16 are the result of logical operations described in figure 9 with controller 17 switching the immersion heater. Controllers 18 and 19 sense operative temperature in controlled zones and actuate respective heating valves for the underfloor system. Similarly controllers 20, 21 and 26 to 28 perform logical operations described in figure 9 for operation of the heat pump and solar collector respectively. Controllers 22 to 25 and 29 to 32 control the operation of the heat pump, solar collector and associated valves.

MODEL CALLIBRATION

The simulation model was subject to calibration against monitored results over a period of several days, tank temperature at various heights and space operative temperature were compared. The calibration process was quantified using statistical goodness of fit metrics described by Williamson (1995). Figure 7 shows these temperatures at heights of one third and two thirds along the water tank and the living space operative temperature at the end of the calibration process. Monitored data is currently only available for winter time and the representative day shown in figure 6 was chosen by visual inspection of water heating patterns over the heating season to ascertain a typical heating and use scenario. Weather data for this day was imposed on the simulation model as were set point temperatures and space and water heating profiles. Table 1 shows statistical goodness of fit results, these were obtained with greater than 95% confidence. Pearson's coefficient is calculated on value (magnitude) and Spearman's coefficient is calculated on rank i.e. how well do the shapes of the two data set match.

Table 1: goodness of fit parameters for predicted tank temperatures at one and two thirds height and space temperature

(a) Mean and standard deviation

		Mean (^{o}C)	Std Dev (^{o}C)
2/3	Monitored	54.8	8.3
	Simulated	50.0	9.2
1/3	Monitored	34.0	8.6
	Simulated	38.8	7.0
Space	Monitored	18.7	0.5
	Simulated	18.5	0.8

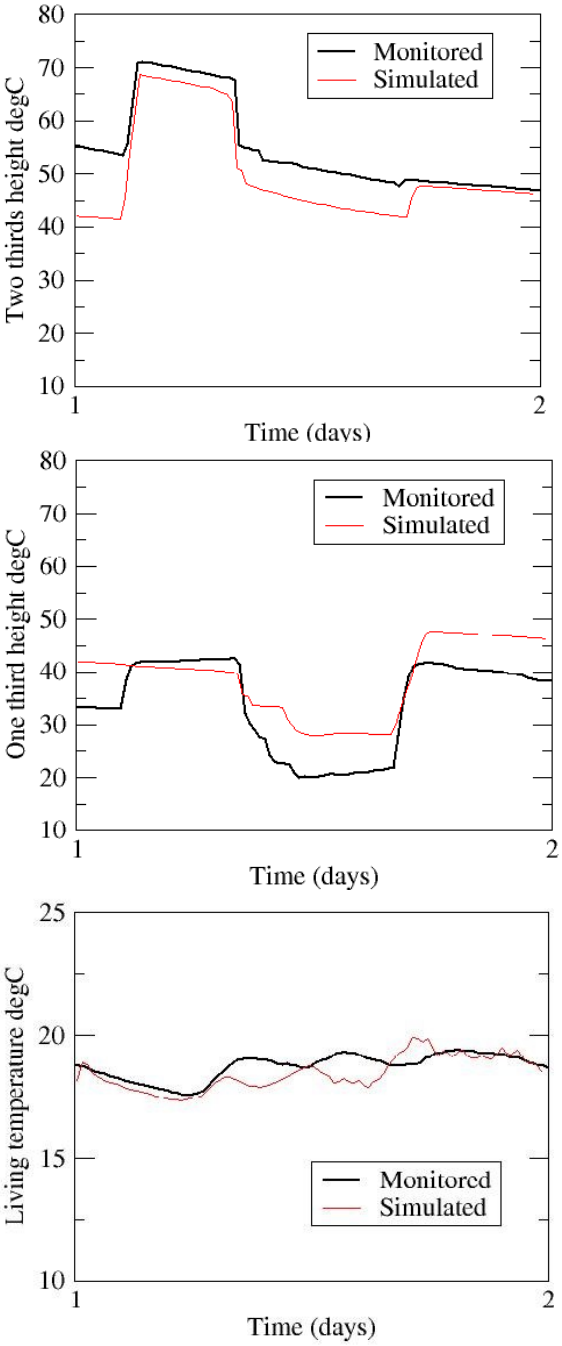

Figure 7 Simulated and monitored temperatures at two and one third height along water tank and operative temperature in the living room

Table 1(b) Correlation coefficients

	RMS error	Normalized RMS error	Pearson's correlation coefficient	Spearman's rank correlation coefficient	Inequality coefficient
2/3	0.63	0.01	0.91	0.42	0.06
1/3	0.65	0.02	0.88	0.58	0.09
Space	0.07	0.00	0.61	0.55	0.02

It was found that whereas calibration of tank heat loss and gain characteristics was relatively straightforward, it was not easy to emulate exact water draw offs. The reason for this is that exact timing and volumes of small water draws are difficult to monitor given the measuring precision of the heat meters employed. This is evident from the divergence between measured and modelled data for the bottom most sections of the tank where impact of fresh makeup water is maximum. Another important observation made during the calibration phase was that the decay rate of the top most section is lowest even though this is the warmest section. This is due to buoyancy driven water movement from lower sections to the upper sections replenishing the top section. Downward buoyance driven flow of cooled water from the tank appear as temperature losses in lower tank sections. Consequently the bottom section of the tank cools more rapidly.

WATER USE PROFILES

Hot water heating load is the biggest thermal load within the dwelling and therefore has the greatest potential benefit regarding shifting. Water heating demand can vary significantly with hot water use. Therefore, a number of hot water usage profiles were considered taking an approach similar to that described for the US context by Hendron *et al* (2010) but adjusted for the UK context. This was imposed as stochastic draw patterns using logic embedded within the modelling software as described by Jordan and Vajen (2005). Daily use profiles were divided into high, medium and low hot water volume used. Further distinction is made between users who stay home the major part of the day and users who stay away during the day time. Still further distinction is made between morning and evening biased users. The complete set of draw profiles for the low usage case is given in figure 8; similar patterns exist for the medium and high volume usage case.

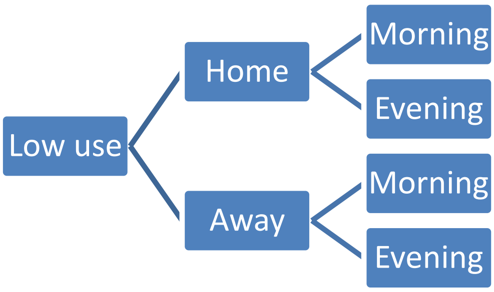

Figure 8 Water use variants: low use case

The levels of actual water usage are taken from EST (2008) where the low, medium and high levels have been equated to the lower quartile, median and upper quartile of UK hot water usage. Figure 9a shows a weekly averaged water draw profile comparing high, medium and low usage morning draw options that shows normalised high draws in the morning and evening with low draws during office hours. Figure 9b compares similar water draw profiles with occupants at home and away; there are lower draws during early morning and evening and higher draws during office hours for ‘at home’. Figure 9c compares a morning biased draw pattern with evening biased draw. These week averaged profiles show how the water draws are profiled; the specifics for a given day can be seen in figure 12.

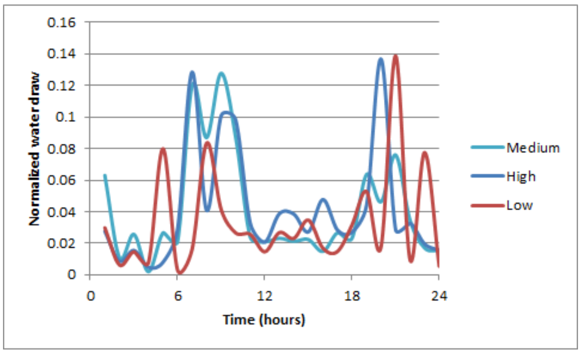

Figure 9a Comparing high, medium and low water draws for occupants away during office hours

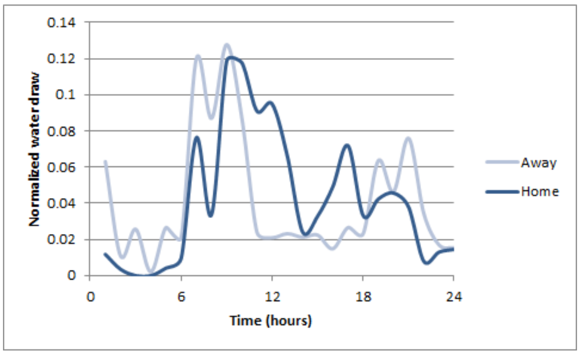

Figure 9b Comparing water draws when occupants are away or at home during office hours

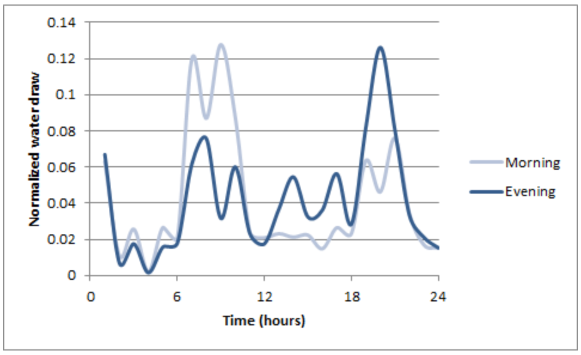

Figure 9c Comparing morning and evening biased water draw profiles

RESULTS

To demonstrate the functionality available through the model, integrated simulations were carried out for three representative weeks during winter, spring and summer. Provision of hot water from the heat pump was constrained to be available only within certain times (in this case between 16:00 and 18:00) to allow its effect on tank temperatures and solar utilization to be clearly shown. The water use profile adopted as a base case is the medium use profile with morning biased draws and occupants away during office hours. While many aspects of system operation can be evaluated, a selection is given here which illustrate the potential useful model outputs.

Figure 10 shows results for the spring simulation. It shows the tank supply temperature (labelled tank top), temperature at the tank bottom and water supply from the heat pump to the tank heat exchanger (labelled ASHP to DHW) and also from the solar collector to the same heat exchanger. It can be seen that for this period there are significant inputs from the solar collector but the heat pump comes on only once i.e. when the tank temperature drops below the set point. Furthermore solar input heats the whole tank because the inlet is placed at the bottom. The sharp rise in tank top temperature on day 5 is because of immersion heater coming on as it follows its weekly schedule. As the immersion heater is at a mid-height in the tank it primarily heats the upper portion of the tank (which makes its effectiveness for tank sterilisation questionable).

This can be compared to the same draw profile when simulated for winter as shown in Figure 11. As expected there is less solar input and heat pump comes on more often. For the summer case (not shown), there are no instances of heat pump charging and all the hot water is serviced by the solar collector for all draw profiles.

These model outputs illustrate the seasonal variation in load shifting possibilities. The heat pump and boost heater can both in theory be used to absorb excess renewable generation when this is available but the amount that can be absorbed will depend on the specifics of the system state. This in turn depends on the solar inputs and the water draw patterns of the occupants. In periods when the potential for solar thermal energy inputs is likely, pre-charging of the water tank will be at the expense of solar inputs, and may eliminate potential gains. The appropriate use of the water tanks as renewable energy buffers is clearly situation specific, dynamic and complex.

Figure 12 shows a more detailed view of tank temperatures and water draw profile for a spring day for the medium use case with morning bias. There is a large draw in the morning and the temperature of all the sections drops but starting at around 0900hours the tank receives solar inputs and comes back up to temperature in time for the evening draws. Figure 13 shows similar data for a winter day. It can be seen that whereas tank temperatures drop for the lower sections as fresh water is drawn to make up for hot water draws the tank top is replenished by warm water from the lower sections and its temperature does not drop significantly with the tank coming up to temperature again after heat pump switches on at 1600hours.

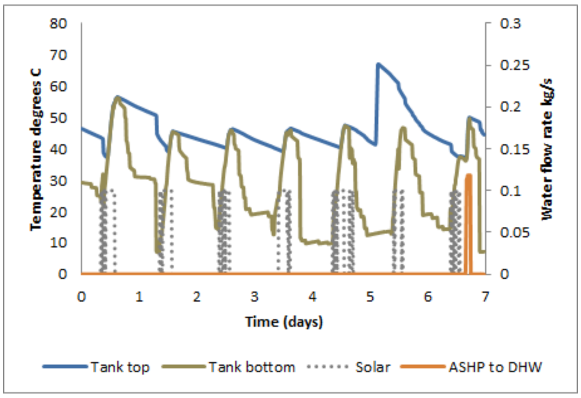

Figure 10 Tank temperature and heat supply to hot water tank, spring case

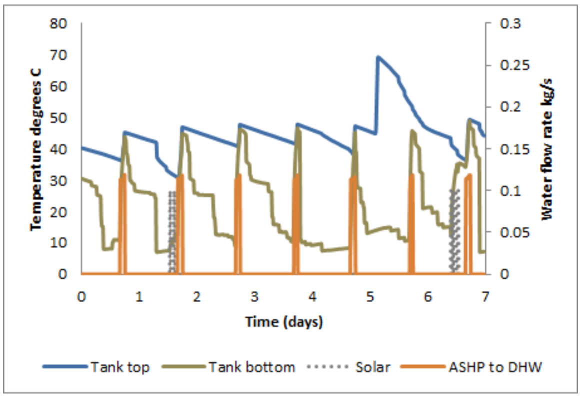

Figure 11 Tank temperature and heat supply to hot water tank, winter case

Figures 12 and 13 show that for the specific water draw patterns on those days, heat from the heat pump is not required for the spring case where solar contributions are made early in the day but is required for the winter day where there is minimal solar energy input.

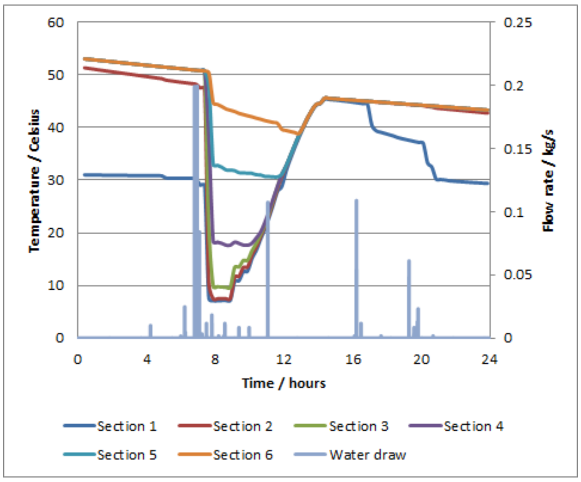

Figure 12 Tank temperatures at various heights and water draw, spring case (6 is top)

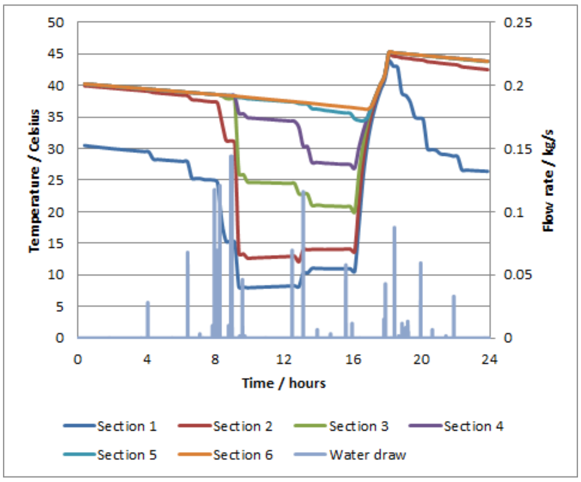

Figure 13 Tank temperatures at various heights and water draw, winter case (6 is top)

Figures 14a and 14b show the same data for the spring simulation as figure 12, but for the high water use case. It is assumed that this is the worst case for solar utilization because most of the draws are made early in the day when there might be no solar availability. Two consecutive days are shown and whereas the system delivers satisfactory heating on the first day, the supply temperature (section 6) is shown to be too low for comfort (< 38^{0}C) on the second day (heat pump held off). This illustrates violation of one of the constraints to be satisfied by any load shifting schema involving domestic hot water systems i.e. the delivery of hot water to meet occupant demands.

Load shifting studies were conducted for the various draw profiles. Winter season was focused on because this affords the most load shifting potential for the heat pump that is the major contributor to water heating during this time. For the base case simulation heat pump operation time is 1600-1800hours for hot water. Figure 11 shows that water heating takes place every day at this time. The water heating schedule was changed to be active at 0000-0200hours, 0600-0800hours and 1000-1200hours and the effect on tank temperatures and energy evaluated.

Figure 15 shows tank temperatures for the four times of operation. It can be seen that the 1000-1200hours case gives lowest temperatures. This situation can be mitigated by enabling the boost heater to become operative whenever the supply temperature drops below 38^{0}C and for brevity is not shown here.

The total energy used for these load shifting studies is given in table 3 that shows that more energy is used when water heating is done earlier rather than later. Such a heating pattern is obtained due to a number of, sometimes conflicting, reasons. These include water draw profile used, state of charging of the hot water tank and heat losses from the tank.

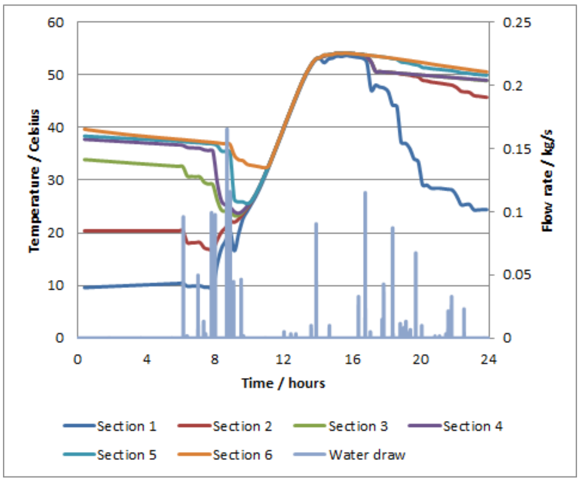

Figure14a Tank temperatures and water draw for spring day for high use, morning bias case. Solar energy easily meets demand.

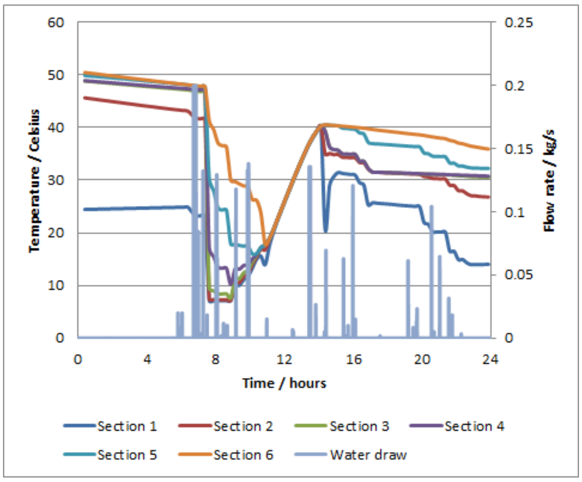

Figure 14b Same as figure 14a but for next day. Solar energy is not sufficient to meet demand and tank temperature falls because heat pump is off.

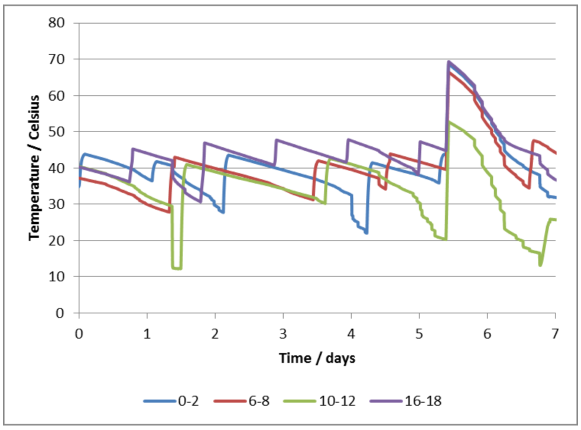

Figure 15 Tank top section (hot water supply) temperatures for different water charging scenarios.

Table 3 Tank heating energy for load shifting cases.

Heating allowed during this time	Heating energy delivered (kWh)
0000-0200	19.7
0600-0800	18.5
1000-1200	13.6
1600-1800	18.0

The requirement then is of a comprehensive parametric analysis to quantify feasible charging schedules, in the context of varying user demands and weather conditions, that:

1. Can be varied daily or in extreme cases more frequently.
2. Consider state of charge of the tank and possible energy and cost implications of remedial measures i.e. boost top up heating that may be required at peak demand hours when there is no renewable energy.
3. Take account of tank heat loss characteristics.
4. Optimize renewable energy utilization.

DISCUSSION

As stated in the introduction the purpose of the simulation modelling approach described here is to underpin various elements of the ORIGIN project i.e.

- Give insights and assist in the quantification of orchestration opportunities,
- Assist in the evaluation of proposed orchestration algorithms,
- Support investigations into improvements in system design to better support load shifting.

The modelling presented here to address these requirements is of necessity detailed and dynamic. This level of modelling is required in order to capture both the system specifics and the variations in weather and user behaviours. These systems and contexts are often presented in literature as simple storage nodes but in reality have complex behaviour that must be considered in detail where a practical implementation is being considered.

The future challenges being addressed in the ORIGIN project are:

1. To develop weather, renewable generation and user demand prediction algorithms that will give a 24hour look ahead.
2. To capture current system state and orchestration opportunities.
3. To determine the appropriate load shifting opportunities to be selected in order to best meet the optimisation objectives (enhanced use of local renewable generation).

These activities are ongoing and the work presented in this paper will provide a test bed to support these activities.

While the work presented here is primarily designed to support the ORIGIN objectives, several elements of the work are in themselves steps forward in the application of integrated modelling of detailed system performance and user behaviours in terms of representative sets of stochastic water draw profiles.

The focus of this paper has been on the hot water storage aspects of load shifting, similar consideration of space heating loads can also be supported by the same general modelling approach.

CONCLUSIONS

A detailed simulation model is developed and presented which has a sufficient level of detail to support load shifting analysis for practical domestic water heating systems of a type which is becoming increasingly common. The model consists of an air source heat pump supplying heat to an underfloor heating system and domestic hot water tank. Also included are a solar thermal collection system and top up / boost immersion heating system. All major thermodynamic domains are explicitly represented in an integrated fashion.

Research is focussed on water heating as this is a major shiftable load. For this purpose a number of water draw profiles are modelled and the effects on draw temperature and solar utilization are studied.

The use of this modelling approach in support of load shifting analysis is proposed and applications discussed.

ACKNOWLEDGEMENT

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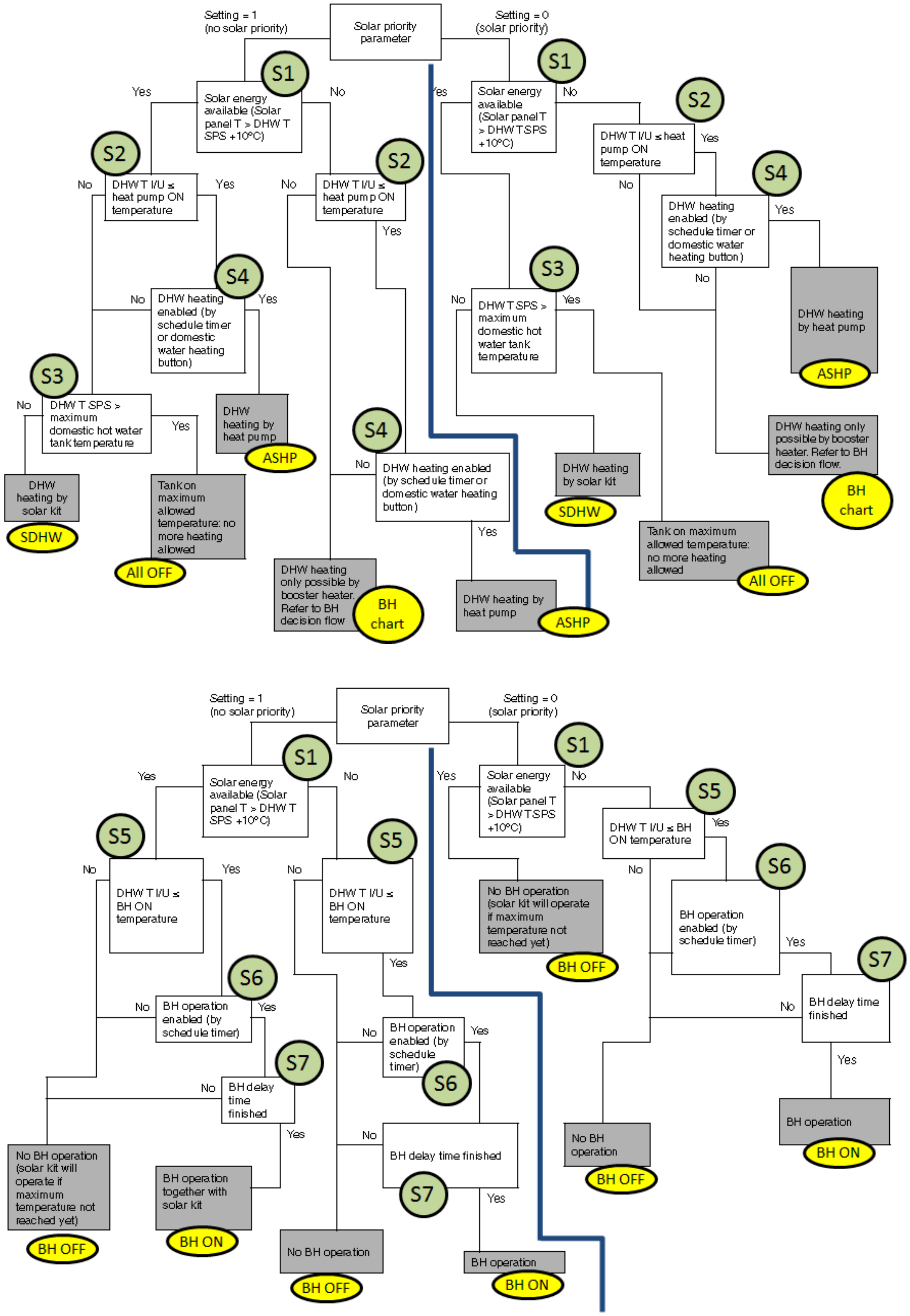

Figure 6 Manufacturer supplied control charts; solar collector control chart at top and boost (immersion) heater (BH) at bottom. These are annotated with required sensors (S1 to S7) and state of final operation (ON/OFF). Abbreviations used are ASHP for heat pump, SDHW for solar domestic hot water and BH for boost (immersion) heater.

Table 2 Control decomposition for heating system, showing contol type, description and control laws used for controlling immersion heater, solar collector and air source heat pump

#	**Control Type**	**Control description**	**Control law**	
1	Sensor	ON if T_SDHW > T_SPS + 10	ON-OFF	**Sensors**
2	Sensor	ON if T_IU <= T_ASHP Flow [ON temperature]	ON-OFF	
3	Sensor	ON if T_SPS > Maximum allowed temperature	ON-OFF	
4	Timer	ON if ASHP timer is ON i.e. 7-9 & 16-23	ON-OFF	
5	Sensor	ON if T_IU <= T_BHON	ON-OFF	
6	Timer	ON if BH timer is ON i.e. 0-6 & 16-24	ON-OFF	
7	Sensor	ON if BH delay time is finished	ON-OFF	
8	Logical operation	!S1		
9	Logical operation	!S2		
10	Logical operation	!S3		
11	Logical operation	!S4		
12	Logical operation	ON if !S1(S8) & !S2(S9)		Boost heater
13	Logical operation	ON if !S1(S8) & S2 & !S4(S11)		
14	Logical operation	ON if S12 | S13		
15*	Logical operation	ON if S5 & S6 & S7 *{no solar priority}* ON if !S1(S8) & S5 & S6 & S7 *{solar priority}*		
16	Logical operation	ON if S14 & S15		
17	Actuator	Sense: S16 Actuate: BH	ON-OFF	
18	Actuator	Sense: Operative Temperature Living Zone Actuate: Zone valve	Proportional	ASHP
19	Actuator	Sense: Operative Temperature Sleeping Zone Actuate: Zone valve	Proportional	
20*	Logical operation	ON if S2 & S4 *{no solar priority}* ON if !S1(S8) & S2 & S4 *{solar priority}*		
21	Logical operation	ON if S18 | S19 | S20		
22	Actuator	Sense: S21 Actuate: ASHP	ON-OFF	
23	Actuator	Sense: S21 Actuate: ASHP Pump	ON-OFF	
24	Actuator	Sense: S20 Actuate: ASHP-DHW valves	ON-OFF	
25	Actuator	Sense: S20 Actuate: ASHP-DHW valves	ON-OFF	
26*	Logical operation	ON if S1 & !S3(S10) & !S2(S9) *{no solar priority}* ON if S1 & !S3(S10) *{solar priority}*		SDHW
27*	Logical operation	ON if S1 & !S3(S10) & S2 & !S4(S11) *{no solar priority}* Always ON *{solar priority}*		
28	Logical operation	ON if S26 | S27		
29	Actuator	Sense: S28 Actuate: SDHW	ON-OFF	
30	Actuator	Sense: S28 Actuate: SDHW Pump	ON-OFF	
31	Actuator	Sense: S28 Actuate: SDHW valves	ON-OFF	
32	Actuator	Sense: S28 Actuate: SDHW valves	ON-OFF	

Abbreviations and Notes:

* These loops change from solar priority case to no solar priority case

Numbers preceded by S represent controller numbers in the table e.g., S12 represent controller 12 in the table

DHW = domestic hot water

SDHW = solar domestic hot water

T_ = temperature of

IU = tank internal unit (at two thirds tank height)

SPS = solar pump station

ASHP = air source heat pump

BH = boost (immersion) heater

BHON = boost (immersion) heater ON set point

& = logical AND function

| = logical OR function

! = logical NOT function