THE EFFECT OF HOT WATER USE PATTERNS ON HEATING LOAD AND DEMAND SHIFTING OPPORTUNITIES

Nick Kelly, Aizaz Samuel, Paul Tuohy
Energy Systems Research Unit,
University of Strathclyde
Glasgow, UK
aizaz.samuel@strath.ac.uk

ABSTRACT

Heating loads for modern houses are lower than older houses with a larger proportion used to service domestic hot water (DHW). Electric heating systems, e.g. air source heat pumps (ASHP) and underfloor heating, offer load shifting possibilities with solar thermal DHW systems providing further opportunities. Other dynamic effects such as heat loss from water tank and stochastic demand need to be considered too.

Hence integrated dynamic simulation is adopted to look at building thermal interactions with explicit plant representation and linked network mass flow and power flow solutions. Stochastic DHW use patterns characteristic of the UK are investigated. Different time controlled heating profiles are simulated to investigate demand shifting.

Findings show user behaviour strongly influences water heating requirements, solar DHW system effectiveness and consequentially load shifting potential

KEYWORDS

Solar domestic hot water, stochastic water use, integrated simulation, model calibration, load shifting, demand side management.

INTRODUCTION

In future energy networks, featuring diverse renewable energy sources, both supply and demand must be orchestrated to ensure a reliable supply of energy to end users. Demand flexibility offered by buildings is the key research area that specifically addresses types of services that offer to support the operation of future networks and how building design must change to accommodate flexible demand. The concept is extensible and the extension desirable to the community level.

The potential of renewable generation to achieve carbon emission savings is severely restricted by the fact that renewable supply is often poorly aligned with energy demand. However, at the community or neighbourhood level, significant opportunities exist for optimising the alignment of renewable supply with community demand. The intention is not to target reductions in total energy use but rather the optimisation of the use of locally generated renewables thus reducing the need to import fossil fuel derived energy. A major load that may be shifted is domestic hot water heating requirement and is chosen to be the example used to demonstrate demand-supply orchestration.

THE ORIGIN SYSTEM

This work was conducted within 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 was 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 possible demand shifting potential. Climatic boundary conditions are also monitored using local weather stations. The ORIGIN system overview is shown in figure 1.

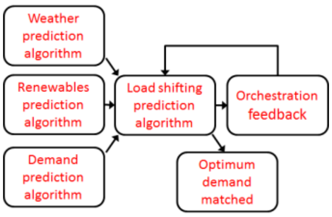


Figure 1 ORIGIN algorithm

The control algorithm for the ORIGIN system relies on automatic acquisition of local weather data from which a weather prediction algorithm generates weather for the near future (24 hours). This is implemented as spatially distributed sensors, data loggers, databases and servers linked by various internet protocols. Monitored data includes dry bulb temperature, direct and diffuse solar radiation and wind speed. Demand predictions are made using regression analysis on previously collected demand data with demand being a function of weather data, time of day and day of week. 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 using a knapsack-filling algorithm.

The simulation modelling described here is to underpin various elements of the ORIGIN project. This includes but is not limited to give insights and assist in the quantification of orchestration opportunities, effectiveness of proposed regressions and to support investigations into improvements in existing systems or design of new systems which better support load shifting in future.

SIMULATION MODEL

Detailed dynamic simulation models were developed at sufficient resolution to provide a test bed for load shifting analysis. These models were used to study various aspects of electrical load shifting with permutations made in DHW demand patterns. To comprehensively assess thermal performance of the building and interactions between fabric, occupants, control and systems an integrated model (e.g. as described by Clarke et al (2012)) was necessary. The following domains are included within this model: building fabric, HVAC plant, solar insolation and shading, mass flow networks for both airflow and water flow in the hydronic circuit and electrical power flow network domains. The building thermal domain was required to account for interaction of the DHW tank with the building. The plant domain was required to model heat and mass flows in the wet hydronic system. Mass flow networks (zonal mass flow method) predicted water flows in the plant and airflows in the building. An electrical network was set up to account for ASHP performance and its effect on the grid.

This form of the model allows the interactions between the different energy subsystems in the building to be accounted for. For example, a sunspace 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 a hydronic plant. To explicitly account for pressure and flow relationships in the plant model, flows were predicted using a hydronic mass flow network. 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 and around the building are modelled by a zonal/network airflow model.

This paper only presents thermal performance of the solar, ASHP hybrid system with DHW storage tank. The importance of variations and uncertainties in behaviours are identified and a set of water draw patterns proposed that are deemed representative of the general population. Finally, a 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 ASHP 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 are well insulated and have lower air leakage rates than older buildings. Hence they are prime candidates for load shifting because of large temperature decay time constants. The potential to post-heat or pre-heat the building or hot water tank is increased as opposed to a standard heating schedule. Moreover within modern domestic buildings heating and cooling may not be the predominant energy loads. A large fraction of the energy is used for provision of hot water and electricity. Hence these offer prime opportunities for load shifting.

The case study simulation model represents a building and hybrid thermal energy system. Such systems are typical in the ORIGIN communities and are becoming more common in general across Europe due to regulatory requirements driving towards higher building energy performance. The model is developed from fabric and systems specifications as described in design documents and was initially calibrated against monitored data. The process involved setting control set points and tuning occupancy profiles.

The focus of the presented work is an apartment from the apartment block shown in Figure 2. The building is modern and follows 2012 Building Regulations (SBS 2012). Extensive monitoring including system and environmental measurements has been conducted and is currently ongoing. Zoning was done following room layout and the apartment was divided into living room, sleeping room, sunspace and roof space. Figures 3 and 4 show wireframe rendering of the apartment and the wet central heating (WCH) system schematic respectively. ESP-r (ESRU 2001) was chosen as the modelling tool. It has extensive integrated simulation capabilities across thermodynamic domains. Details of individual domain solutions are readily available (ESRU 2001) and details of domain integration may be found in Clarke and Tang (2004).

The actual dwelling is very airtight and highly insulated; it benefits from a mechanical heat recovery ventilation. The WCH system consisting of a low temperature ASHP supplying both space and water heating. The whole dwelling is heated by means of underfloor heating except the sunspace which has not heat distributor. DHW provision is by means of a hot water storage tank. This tank may also simultaneously provide water for space heating. The tank may be heated by the ASHP or alternatively from a solar thermal system. The tank also houses a boost immersion heater that is used if the tank temperature drops below a set point. This heater also comes on weekly to satisfy hygiene obligations regarding legionella bacteria. Both ASHP and the solar DHW system cannot operate simultaneously but the boost heater is independent of both.

Figure 2 Findhorn vilage and apartment block (monitoring site)

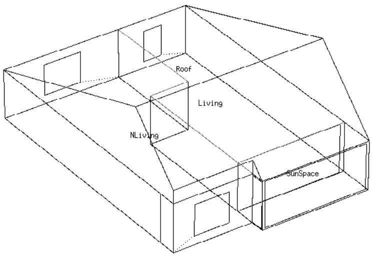


Figure 3 ESP-r dynamic thermal model

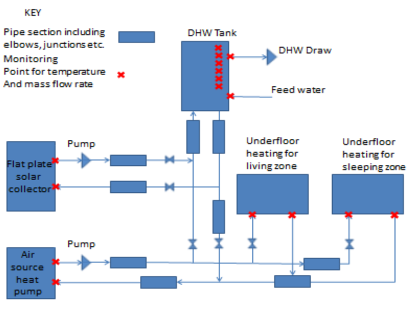


Figure 4 Explicit plant model schematic

The standard network flow analysis (zonal mass flow method) (Lorenzetti 2002) was used to predict flow in the hydronic system. The network flow model was necessary so that the water pump pressure flow relationships (Grundfos 2005) could be explicitly accounted for. This was coupled with the plant network that described energy and mass flows within the systems domain. It was important to model water stratification within the tank and solar thermal collection. ESP-r provides a means to do this via explicit plant modelling of storage tanks (Wang et al 2007) and dynamic solar thermal collection (Thevenard et al 2004). Hence a coupled plant and flow model was developed and simulated in parallel with the building model. These plant and water flow domains were run at a small time step (typically 0.5 minutes) because of lower thermal capacitance. The building and air flow domains were run at a larger time step (typically 5 minutes).

CONTROLS MODELLING

The water tank manufacturer has provided details regarding heating control in the installation and operation manual (Daikin 2010). Recommendations regarding set points and operating ranges for operation of solar collector, ASHP and immersion heater are provided. The decision flow diagram for operation of solar and top up immersion heating is shown in figure 5. The solar collector is set to operate whenever its temperature is 10^{o}C (or more) higher than the tank inlet point. The ASHP is time controlled to heat water between 0700-0900 and 1600-2300. This is the manufacturer's recommendation but within the study this was changed in order to study system performance when shifting loads and is described later. Top up heating is provided by the immersion heater which is scheduled to be operated once a week for one hour ostensibly for legionella treatment.

In figure 5 the abbreviations S1 to S7 represent the seven sensors that are required within the simulation model for implementing the recommended control. It was necessary to decompose the manufacturer provided control logic to a digital (ON/OFF) format. Implementation within the simulation environment is described in table 2. The first seven controllers (1-7) in the table are sensors S1 to S7 described in Figure 5. The next four controllers (8-11) represent the logical inverse of controllers 1 to 4 and make further control convenient. The next set of controllers (12-16) result from various logical operations described in the table. It should be noted that all these controllers only sense conditions or determine the results of logical outcomes based on various sensed conditions. They do not actuate any building or plant components.

Controller 17 is the first actuating controller and switches the immersion heater. The next two controllers (18, 19) represent thermostats in the controlled zones; these sense operative temperature and actuate heating valves for the respective underfloor systems. Further logical operations described in figure 5 are done by controllers 20, 21 and 26-28. This results in actuation of the ASHP and solar collector. Actuation of the ASHP and the solar collector is done by controllers 22-25 and 29-32.

MODEL CALLIBRATION

Monitored data for several days was used to calibrate the model. This included temperatures along the height of the tank and operative temperature. Figure 6

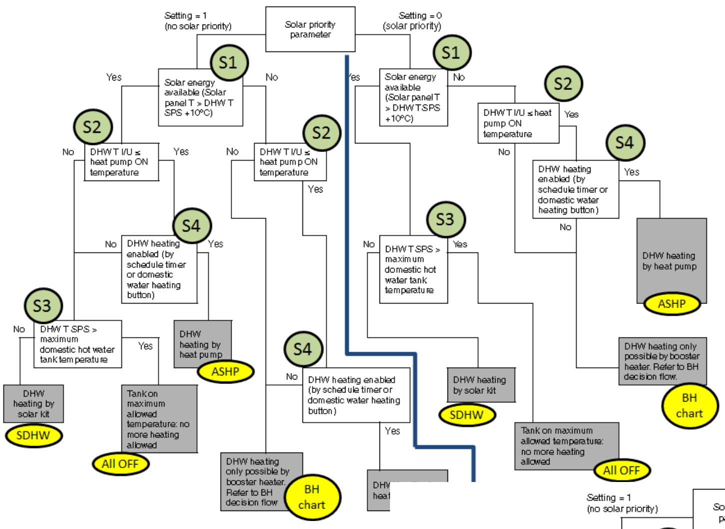
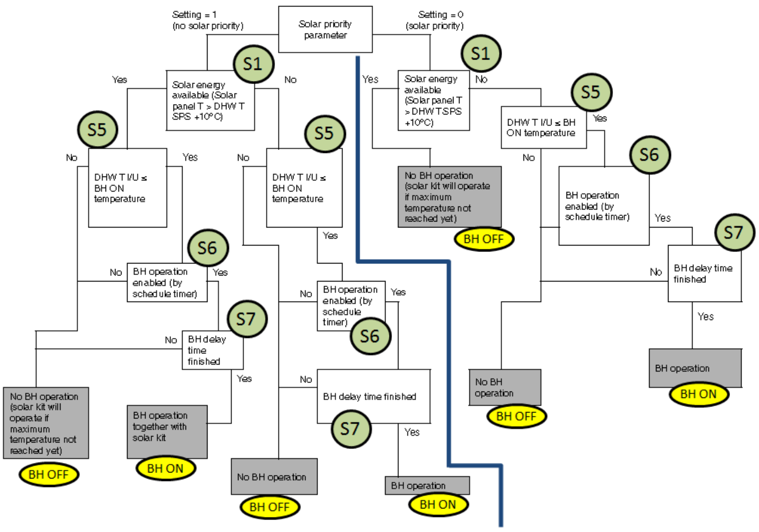


Figure 5 Manufacturer supplied control charts; solar collector control chart at top and boost (immersion) heater (BH)at bottom. These are annotated with required sensors (S1 to S7)and state of final operation (ON/OFF).



Abbreviations used:

ASHP = heat pump,

SDHW = solar domestic hot water

BH = boost (immersion) heater.

shows the operative temperature and temperatures at two representative heights of one third and two thirds along the tank. The figure shows results for a representative day chosen by visually comparing heating patterns over the winter season to determine typical water heating and use scenarios.

Statistical goodness of fit metrics were used to judge the calibration (Williamson 1995). Table 1 shows the comparisons which were all obtained with greater than 95% confidence. Pearson's coefficient is calculated on value i.e. magnitude of the measurement and Spearman's coefficient is calculated on rank i.e. how well do the shapes of the two data sets match. Tank heat loss and gain characteristics could be calibrated easily but water draws were difficult to match in the simulation model. The single largest reason for this is that the resolution of the heat meters used was not fine enough to give desired monitoring precision. The impact of fresh water inlet is highest at the lowest levels of the tank and hence divergence between measured and modelled data for this section is maximum. The decay rate for the top most section is lowest even though it is hottest. This is due to buoyancy driven water movement from lower sections to the upper sections replenishing the top section and downward 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

The biggest heating load for the dwelling is DHW and this has the greatest potential for load shifting. Demand varies significantly with hot water use patterns. Therefore hot water usage profiles were described in an approach similar Hendron et al (2010) who have studied the US context. It was adjusted for the UK and stochastic water draw patterns were imposed in the model using embedded DHWcalc logic (Jordan and Vegan, 2005). Three high level water use profiles were defined these being high, medium and low. Further division is made for users who stay home mostly and those who stay away during the daytime. The final division is made for morning and evening biased users.

Actual water usage data are taken from EST (2008) where the low, medium and high levels have been taken as the lower quartile, median and upper quartile of the national average UK hot water usage. Figure 7 shows these water draw profiles for a typical week . It compares high, medium and low usage morning draw options. Figure 8 compares similar water draw profiles with occupants at home and away. Figure 9 compares a morning and evening biased draw patterns.

Table 1: goodness of fit parameters for comparing simulation vs measured data. Tank temperatures (°C) at 1/3 and 2/3 height and operative temperature (OT)

(a) Mean and standard deviation

		Mean	Std Dev
2/3	Monitored	54.8	8.3
	Simulated	50.0	9.2
1/3	Monitored	34.0	8.6
	Simulated	38.8	7.0
OT	Monitored	18.7	0.5
	Simulated	18.5	0.8

(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
OT	0.07	0.00	0.61	0.55	0.02

RESULTS

Integrated simulations were carried out for three weeks during winter, spring and summer, for each of the water draw profiles. The ASHP was constrained to operate only between 16:00 and 18:00 to allow its effect on tank temperatures and solar utilization to be clearly shown. The base case model is the medium use profile with morning biased draws and occupants away during office hours. While it is possible to evaluate a variety of system operation aspects, a selection is given here to illustrate the potentially useful model outputs.

Spring simulation results are shown in figure 10. It shows the tank supply temperature (labelled tank top), temperature at the tank bottom and water supply from the ASHP 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 ASHP 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 situated 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 mid-height of the tank it primarily heats the upper portion of the tank (which makes its effectiveness regarding tank sterilisation questionable).

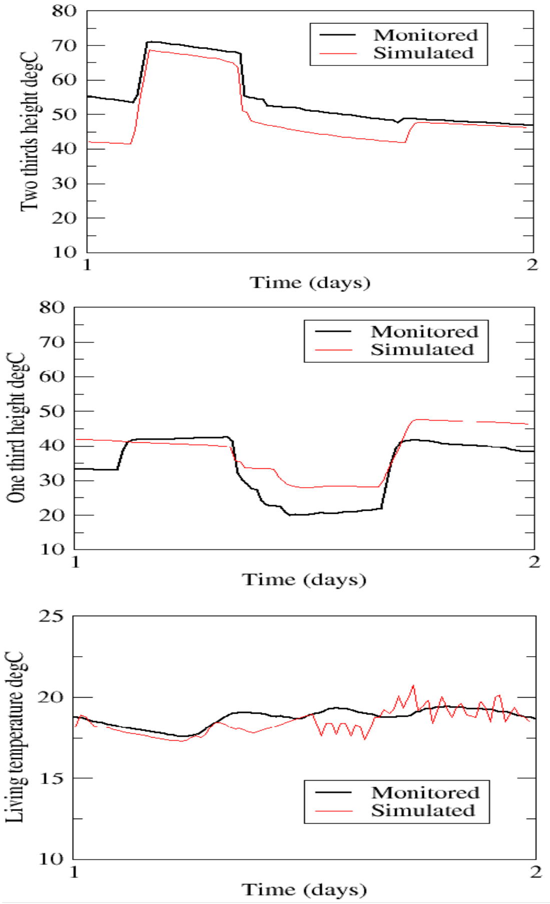


Figure 6 Simulated and monitored temperatures at two and one third height along water tank and operative temperature in the living room

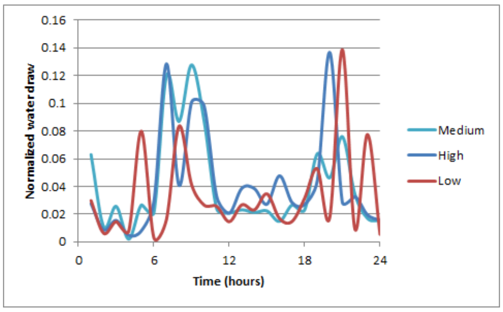


Figure 7 Comparing high, medium and low water draws for occupants away during office hours

This can be compared to results from the same draw profile when simulated for winter as shown in Figure 11. As expected, there is less solar input and ASHP comes on more often. For the summer case (not shown), there are no instances of ASHP 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 ASHP 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

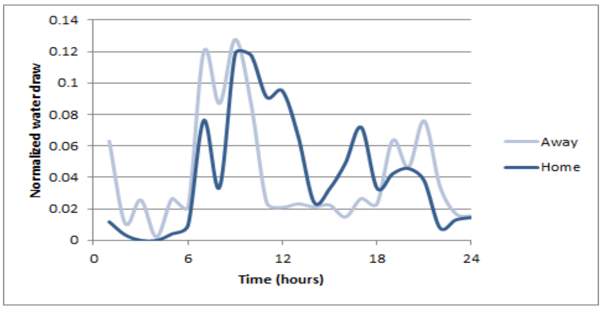


Figure 8 Comparing water draws when occupants are away or at home during office hours

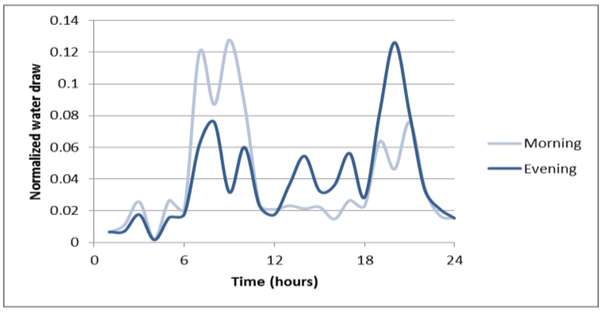


Figure 9 Comparing morning and evening biased water draw profiles

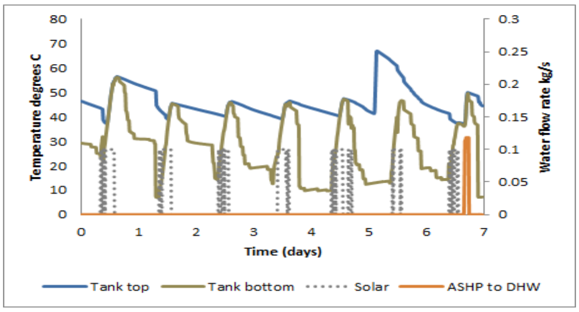


Figure 10 Tank temperature and heat supply to hot water tank, spring case

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 0900 hours 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 ASHP switches on at 1600 hours.

Figures 12 and 13 show that for the specific water draw patterns on those days, heat from the ASHP 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.

Figures 14a and 14b show the same data for the spring simulation, 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 (ASHP held off). This illustrates violation of one of the constraints to be satisfied by any load-shifting schema involving

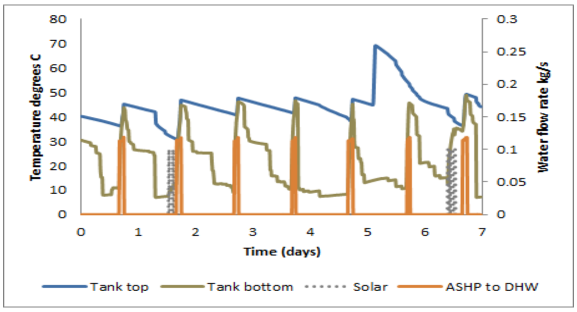


Figure 11 Tank temperature and heat supply to hot water tank, winter case

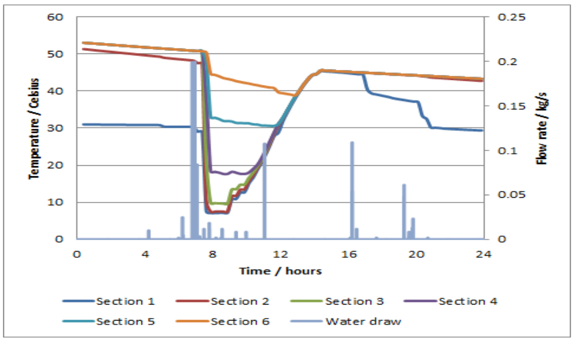


Figure 12 Tank temperatures at various heights and water draw, spring case

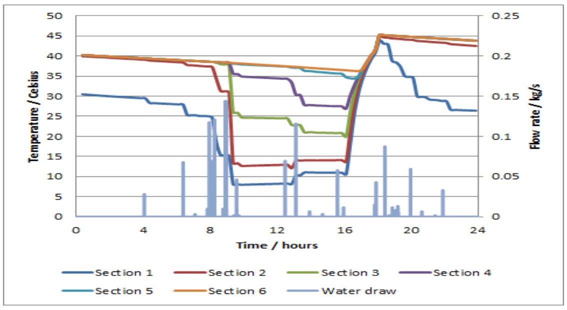


Figure 13 Tank temperatures at various heights and water draw, winter case (6 is top)

domestic hot water systems i.e. the delivery of hot water to meet occupant demands.

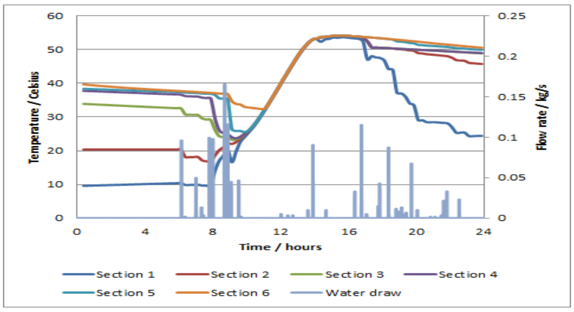


Figure14a Tank temperatures and water draw for spring day for high use, morning bias case. Solar energy easily meets demand.

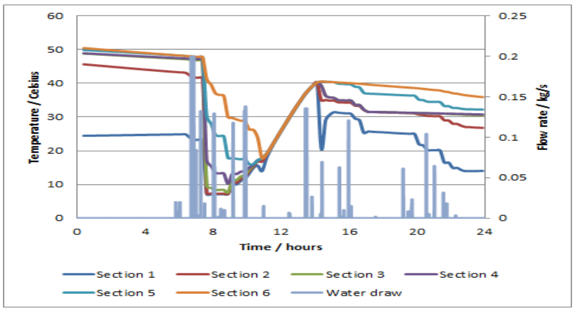


Figure 14b As figure 14a but for next day. Solar energy is not sufficient to meet demand and tank temperature falls because ASHP is off.

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.; provide insights and assist in the quantification of orchestration opportunities; assist in the evaluation of proposed orchestration algorithms and 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 and represent reality. 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.

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 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 sufficient level of detail to support load-shifting analysis for practical domestic water heating systems of a type that is becoming increasingly common. The model consists of an ASHP 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 shift-able 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

Grateful acknowledgement is made to the European Union Seventh Framework Programme (EU FP7) for funding made available to conduct this research within their project titled “Orchestration of Renewable Integrated Generation in Neighbourhoods” (ORIGIN).

REFERENCES

Clarke, J.A., Hand, J.W., Kelly, N., Malik, A., Samuel, A., Strachan, P.A. and Tuohy, P.G. 2012. ‘A data model for integrated building performance simulation’, Proc. Building Simulation and Optimisation Conf., University of Loughborough.

Clarke J and Tang D (2004). A co-operating solver approach to building simulation. Proc. ESim '04, Vancouver, Canada.

Daikin (2010). Solar kit for air to water heat pump system. Installation and Operation Manual. Altherma by Daikin. EKSOLHWAV1. Daikin London, UK.

ESRU (2001). ESP-r building simulation program. Energy Systems Research Unit. www.strath.ac.uk/esru (accessed 15/01/2014).

EST (2008). Measurement of domestic hot water consumption in dwellings. Energy Savings Trust final report for Department for Environment, Food and Rural Affairs (DEFRA), UK. Crown Copyright 2008.

Grundfos 2005. Technical Data Sheet. Grundfos. uk.grundfos.com/content/dam/UK/Brochure/UPS 2%20datasheet%20revised%201812%20.pdf (accessed 26/04/2014)

Hand J (2011). The ESP-r Cookbook. Strategies for Deploying Virtual Representations of the Built

Environment. Energy Systems Research Unit, University of Strathclyde, UK.

Hendron B, Burch J and Barker G (2010). Tool for generating realistic residential hot water event schedules. Proc. SimBuild 2010, New York, USA.

Jordan U, Vajen K (2005). DHWcalc; Program to generate domestic hot water profiles with statistical means for user defined conditions. Proc. ISES Solar World Congress, Orlando (US), 8. - 12.8.2005

Lorenzetti, D. M. 2002. Computational Aspects of Nodal Multizone Airflow Systems. Building and Environment 37 (2002).

SBS (2012). Scottish Building Standards. www.scotland.gov.uk/Topics/Built-Environment/Building/Building-standards (accessed 26/04/2014).

Thevenard D, Haddad K and Purdy J (2004). Development of a new solar collector model in ESP-r. Canadian Solar Buildings Conference, Montreal, Canada.

URL 1 (2014). http://www.origin-energy.eu/ (accessed 07/04/2014)

Wang W, Beausoleil-Morrison I, Thomas M, Ferguson A (2007). Validation of a fully mixed model for simulating gas fired water storage tanks. Proc. Building Simulation 2007, Beijing, China.

Williamson T (1995). A confirmation technique for thermal performance simulation models. Building Simulation 1995, Wisconsin, USA.

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

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

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

DHW = domestic hot water   SPS = solar pump station   T_ = temperature of

BH = boost (immersion) heater   ASHP = air source heat pump   SDHW = solar domestic hot water

IU = tank internal unit (at two thirds tank height)   BHON = boost (immersion) heater ON set point

T_op_Liv = living space operative temperature   T_op_Slp = Sleeping space operative temperature